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EXPERIMENTAL STUDIES OF COLDWORKED FASTENER HOLES

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Final Report

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report summarizes the accomplishments of this research and catalogs its resulting papers and reports. When an oversized mandrel is pulled through a hole, the material near the hole edge is coldworked. After the mandrel is removed, the elastic restoring forces of material away from the hole generate compressive stresses at the edge. Subsequent tensile loading must overcome the compressive edge stresses, so a consderable improvement in the ultimate or fatigue loading capability of a structure can be achieved. The research was performed in four phases: Phase I-Measurement of the residual strains around coldworked holes. Phase II-Measurement of the location of the

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boundary between the elastic and plastic regions around the hole. Phase III-A study of fatigue crack initiation and growth from coldworked and noncoldworked holes. Phase IV-A study, similar to Phase III, of holes that had existing cracks and were then coldworked.

INTRODUCTION

This report gives an overview of the AFOSR-sponsored research on coldworked fastener holes conducted at Michigan State University between 1 March 1975 and 31 December 1977.

When a hole in a sheet or plate of metal is expanded radially until plastic deformation occurs at the edge, removal of the expanding forces causes the material at the edge to go into a stress state of compression. The elastic recovery of the rest of the component or specimen generates this compression. Any subsequent static or fatigue tensile loading must overcome the compressive stress at the hole edge; hence, the load-carrying capacity of the structure (either static ultimate load or fatigue life) is enhanced. This process of plastically expanding a hole is known as coldworking.

A design procedure in which one specifies the amount of coldworking in order to achieve a certain fatigue life for a coldworked hole is really the long-term goal of research in this area. For this procedure to be sufficiently accurate and reliable, one must have confidence in each step of the prediction; i.e. residual stresses, crack initiation, crack growth, effects of spectral loading, etc. The purpose of this research program has been to experimentally study the residual stresses, crack initiation, and crack growth of coldworked holes.

There are approximately 1.2 million fasteners (rivets, bolts, etc.) in a commercial aircraft such as the L-1011. In addition, there are numerous open holes in the structure for wiring, hydraulic hoses, etc. Each of these is a stress-concentration that is a potential site for crack initiation. Coldworking is a way of improving the crack-resistance of a fastener or open hole. Furthermore, cracks are found in routine inspections of older aircraft, e.g. B-52's, and coldworking is a useful repair procedure. The Air Force's damage tolerant design procedure (1) requires consideration of cracks at fasteners as well as the traditional static and fatigue design requirements. Clearly a thorough understanding of the useful features and limitations of coldworking is desirable.

Research on coldworked holes has been primarily of two types: fatigue tests that explore the effects of various parameters (hole size, material, etc.) on the life of specimens, e.g. (2), or theoretical studies of the mechanics of elasto-plastic deformation around the coldworked hole, e.g. (3). In terms of design of aircraft structures, one would like to understand the effects of various parameters on the stress state around the hole and the relation of this stress state to the fatigue life, i.e. a joining of the two research approaches. One recent paper (4) has done this with satisfactory agreement. In order to have full confidence in the coldworking process, one must look not only at the final result--the fatigue life--, but must ascertain whether the theoretical predictions of the stress state are accurate. This residual stress state around the hole is important because there is concern about increased stress-corrosion cracking due to residual tensile stresses away from the holes (5).

A particular coldworking process was chosen for use in this research because it had been recently molded in an elasto-plastic finite-element study (6). The coldworking process studied is schematically illustrated in Figure 1. A thin-walled sleeve is first inserted into the hole and then a tapered mandrel is pulled through the sleeve. The mandrel is pulled through with a hand-held hydraulic ram, which has a special head that grips the smaller end of the mandrel. A small washer attached to the sleeve protects the structure from scratches, and this washer is removed after the process is completed. The sleeve may or may not be left in the hole; in a repair operation it is used to restore the hole to its original dimension. All experiments were conducted on 7075-T6 aluminum.

The research performed on this program may be divided into four parts:

- Part I Strain Measurements around Coldworked Holes.
- Part II Elastic-Plastic Boundary Measurements
- Part III Crack Initiation and Growth
- Part IV Coldworking of Precracked Holes

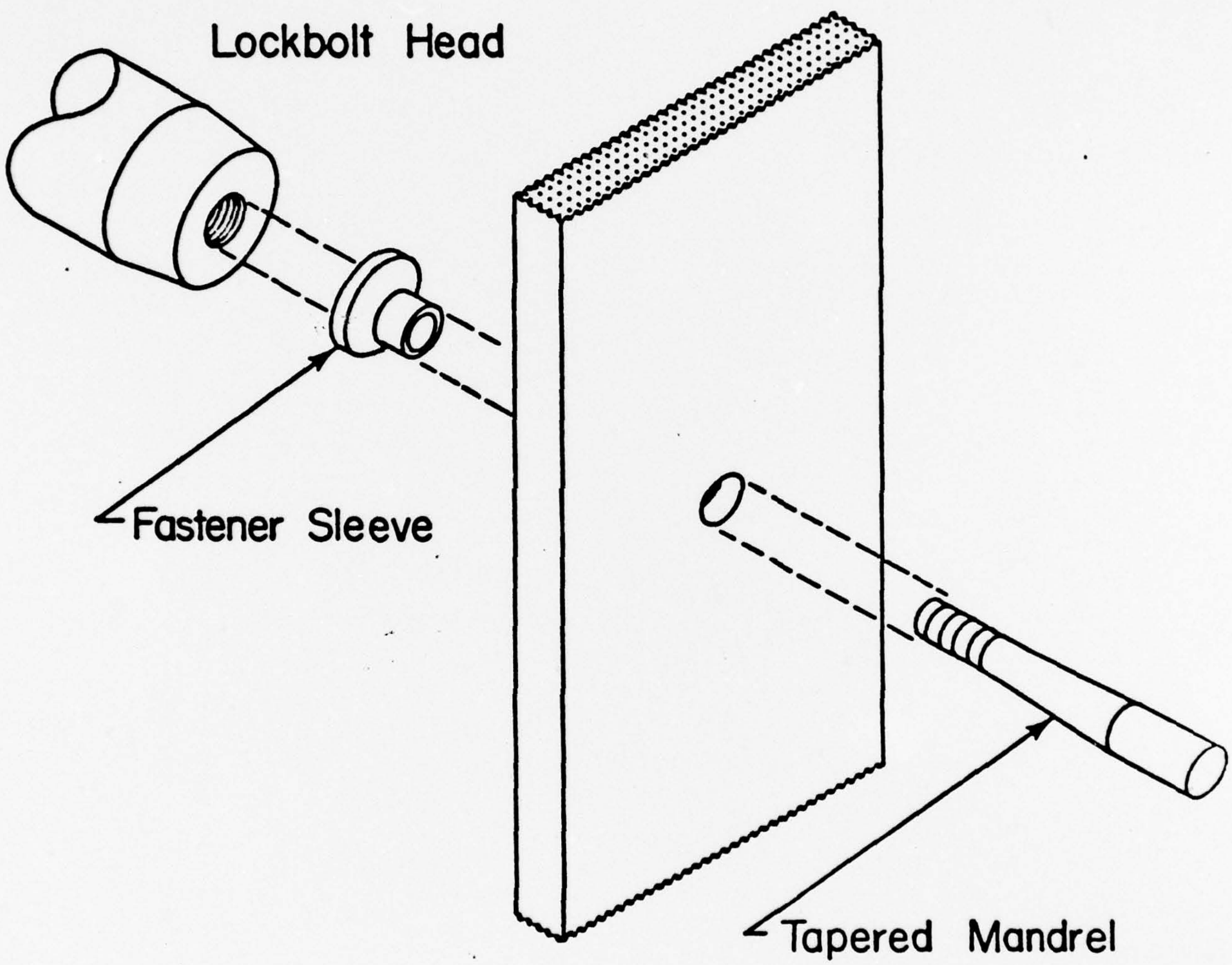

Figure 1. Schematic of the coldworking process.

In this report, these parts are summarized in the following four sections. Each section describes the most significant accomplishments and lists the publications that give more detail. The final section contains some concluding remarks.

PART I -- RESIDUAL STRAIN MEASUREMENT -- March 1975 to March 1976

References--The results of this part of the program are presented in:

Sharpe, W. N., Jr., "Measurement of Residual Strains around Coldworked Fastener Holes," AFOSR-TR-77-0020, 82 pgs.

Sharpe, W. N., Jr., "Residual Strains around Coldworked Fastener Holes," Journal of Engineering Materials and Technology, in press.

This latter paper will be presented at the Eighth U.S. National Congress of Applied Mechanics in June, 1978. In addition, the initial results were presented at a seminar at AFML in November 1975. Three meetings on this problem were held with Captains A. F. Grandt and R. M. Potter during 1975-1976.

Additional measurements of residual strain are reported in the Masters thesis of Miss Sue Emery and in an AFOSR Scientific Report entitled, "Residual Strains around Holes Expanded with a Three-Roller Device".

Summary

The purpose of Part I was to measure the residual strains around a coldworked hole and compare them with the strains predicted by existing theories. The primary efforts were:

a) select or develop a suitable measurement technique
b) literature search and review of theories
c) comparison of theory and experiment.

The coldworking process used for 6.6 mm holes produces plastic residual radial strains that vary from $\sim$7 percent at the hole edge to $\sim$0.1 percent 4 mm from the edge. This is a difficult experimental mechanics problem because the strains and the gradient of strains are quite large. Furthermore, the 7075-T6 aluminum has large grains which dictates that several measurements must be taken to average out the effects of inhomogeneous deformation. Standard techniques such as foil gages, Moiré methods, and photoelastic coating were evaluated and discarded. Strains were measured by placing small indentations in a pattern on the specimen with a Vicker's hardness tester and measuring the distance between them before and after deformation with a microscope. This is a tedious procedure, but it yields good results over a very short (200 microns) gage length and very close (50 microns) to the hole edge.

Nine different theoretical predictions (3, 5-12) of the residuals stress-strain state around a radially expanded and unloaded hole were considered; these are all described and referenced in the technical report. They range from the perfectly plastic analysis of Nadai in 1943 to the nonlinear workhardening analysis of Hsu-Forman in 1975. Included in these nine is the elastic-plastic finite element solution of Adler-Dupree which was obtained for the same material and amount of expansion used in the experiments.

The experimental strains for three different specimen thicknesses are compared with the four theories that gave closest agreement in Figures 2 and 3. Additional information about the deformation is contained in the technical report.

For the radial strains of Figure 2, the finite-element solution of Adler-Dupree (4) predicts the strain very well for the thinner specimens at distances of more than 1 mm from the hole edge. This leads to two observations: a) the 6.4 mm specimen is not in a state of plane stress, and b) the complicated deformation of the expanded hole looks like a uniform radial expansion if one moves far enough away from the edge of the hole. Note how close together the Nadai and Hsu-Forman theories are in spite of their differences in material behavior representation, yield criteria, and computational technique.

None of the theories agree with the residual tangential strain data of Figure 3. The experimental data is more-or-less the same regardless of the specimen thickness; there is no

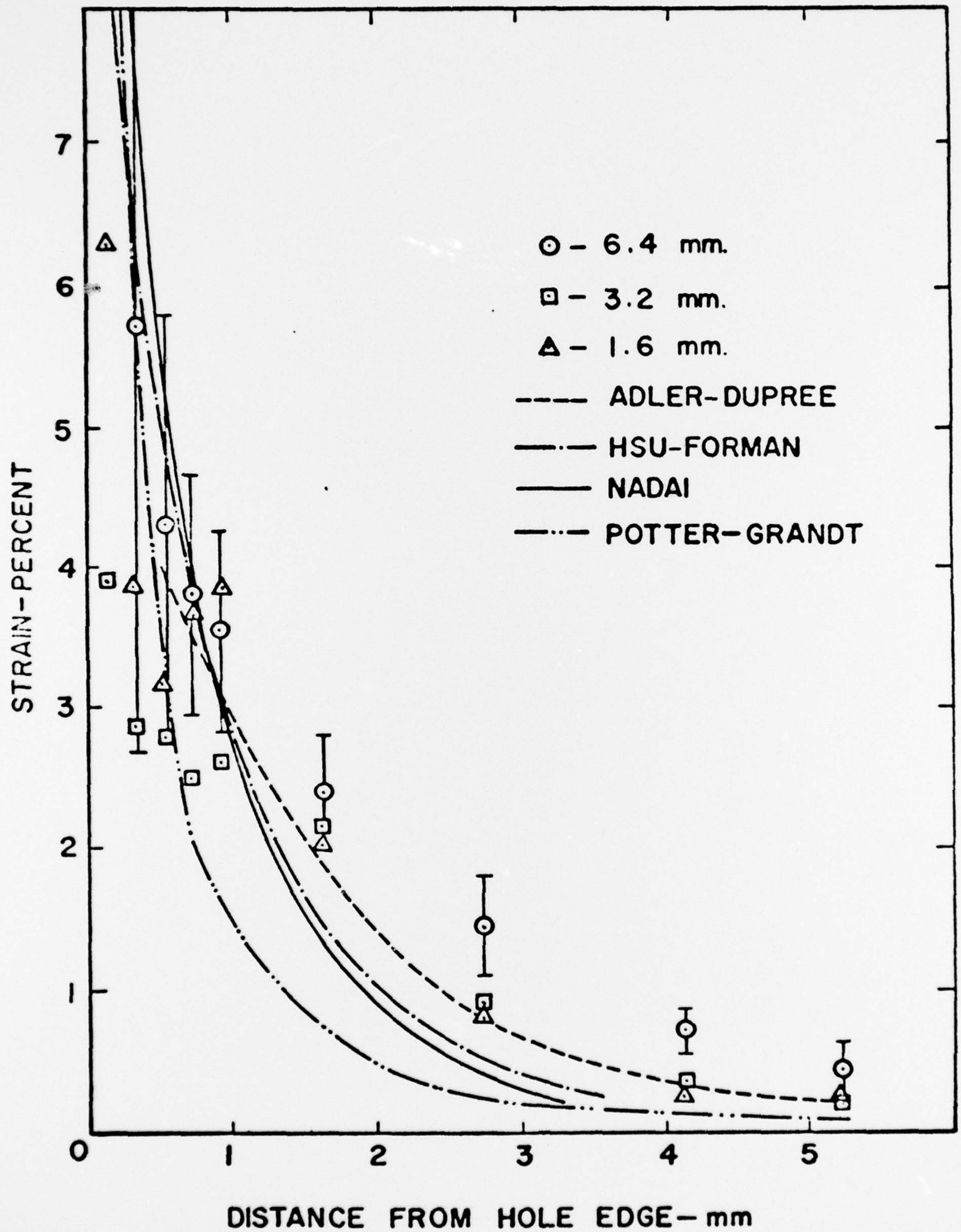

Figure 2. Comparison of measured residual tangential strains (tension) for three thicknesses of 7075-T6 aluminum with four theories. The 6.6 mm diameter hole was expanded to 0.3 mm.

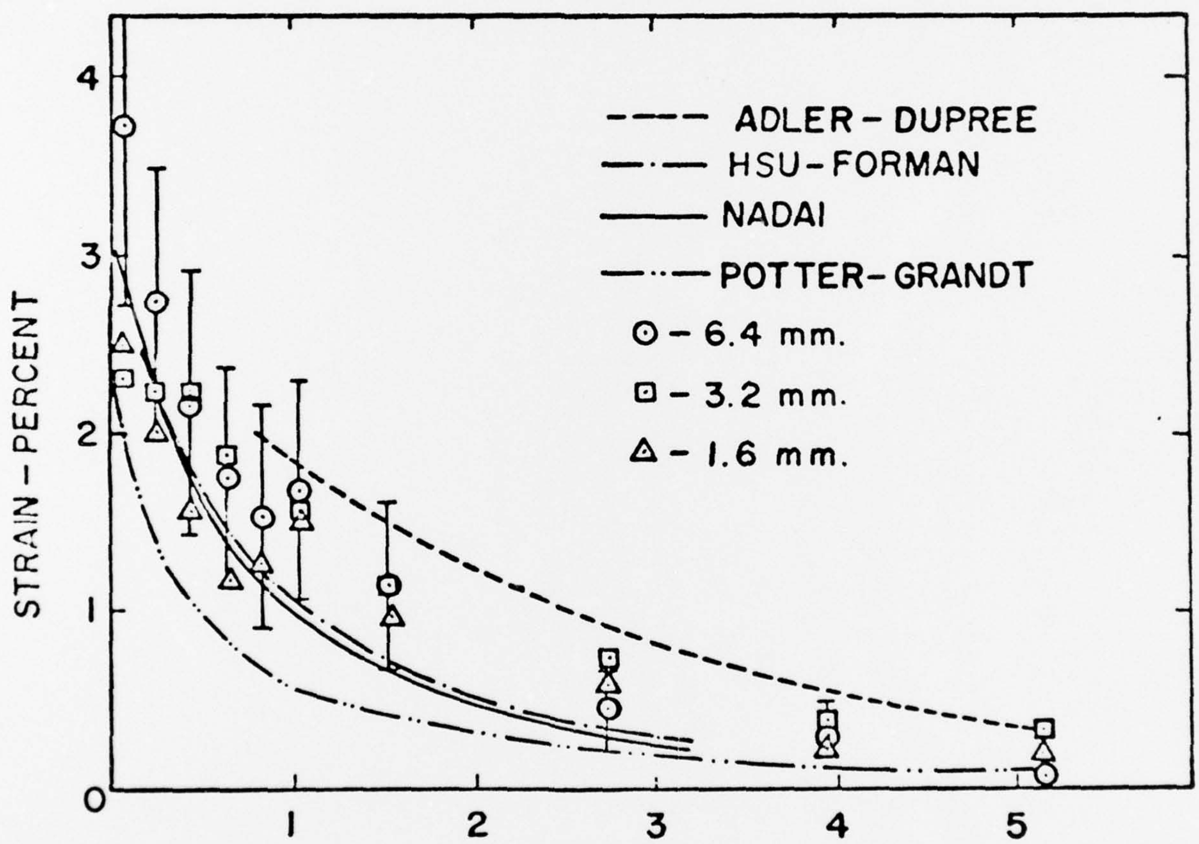

Figure 3. Comparison of measured residual radial strains (compression) for three thicknesses of 7075-T6 aluminum with four theories. The 6.6 mm diameter hole was expanded 0.3 mm.

clear separation of the 6.4 mm thick data from the other two. It is somewhat disturbing that the Adler-Dupree tangential strain prediction is not in closer agreement. Their predictions are different in the following way: all other theories and all experimental results show the residual strain to be always greater than or equal to the tangential strain; they show the opposite away from the hole. If the material in the plastic zone is incompressible, their result means that the specimen is thinner than it originally was.

The theories do not predict the residual strains very accurately. All of the theories indicate the same trends, but do not give close agreement with the average residual behavior. This implies that the theories would not be very useful in predicting the increase in fatigue life. They would be useful in selecting spacing of coldworked holes to avoid interactions. The cold-worked hole is a difficult problem analytically because of the three-dimensional effects.

Miss Emery's thesis dealt with the measurement of strains around holes (12 mm in diameter) that were expanded with a three-roller device of the type described in Nadai's paper (7). It was hoped that this expansion technique would give uniform strains through the thickness, but it did not.

PART II -- ELASTIC-PLASTIC BOUNDARY MEASUREMENTS

References--This phase of the research is reported in the Ph.D. thesis of:

Captain S. Poolsuk, Royal Thai Air Force entitled "Measurement of the Elastic-Plastic Boundary around Coldworked Fastener Holes".

A paper with the same title by S. Poolsuk and W. N. Sharpe, Jr. has been accepted for publication in the Journal of Applied Mechanics. This work will be submitted for presentation at the Winter Annual Meeting of A.S.M.E. in 1978.

Summary

The purpose of this work was to compare the measured location of the interface between elastic and plastic deformation with the

location predicted by theories. This is in contrast to Part I which compared the strains. Elastic-plastic boundary measurements should be simpler and the comparison better because the boundary is approximately 6 mm from the large deformation at the hole edge. In other words, looking at the boundary location is a coarser view of the problem.

The nature of the radial expansion problem is such that as long as there is no plastic deformation there is no change in thickness of the plate. So, the elastic-plastic boundary is located where the thickness begins to change as one approaches the hole. A thickess-measuring instrument was constructed using a LVDT; it measured the relative, not the absolute thickness. It produced a plot of thickness versus distance from the hole edge. The elastic-plastic boundary was identified by the position where the thickness changed by a certain amount. To check the accuracy of this method, three small foil gages were placed along radial lines, and the boundary was located from strain measurements. The thickness-measurement technique is much easier and cheaper, and was used for the more than 50 measurements on two thicknesses of 7075-T6.

The theories used were taken from those of Part I plus two more recent ones (4, 13) based on plane strain deformation. In each case the variation of the boundary location, r_p, with radial expansion was plotted.

The composite comparison plot for the two thicknesses is presented in Figure 4. The main conclusions from this part are:

The thickness-measurement technique of locating the elastic-plastic boundary works well for this particular geometry. It agrees with measurements obtained by foil gages and is much easier. It measures an average (through the specimen) value which is appropriate for comparison with the continuum mechanics theories.

The slope of the boundary versus radial expansion curve decreases with increasing expansion indicating that an optimum value of expansion could be selected. Fatigue

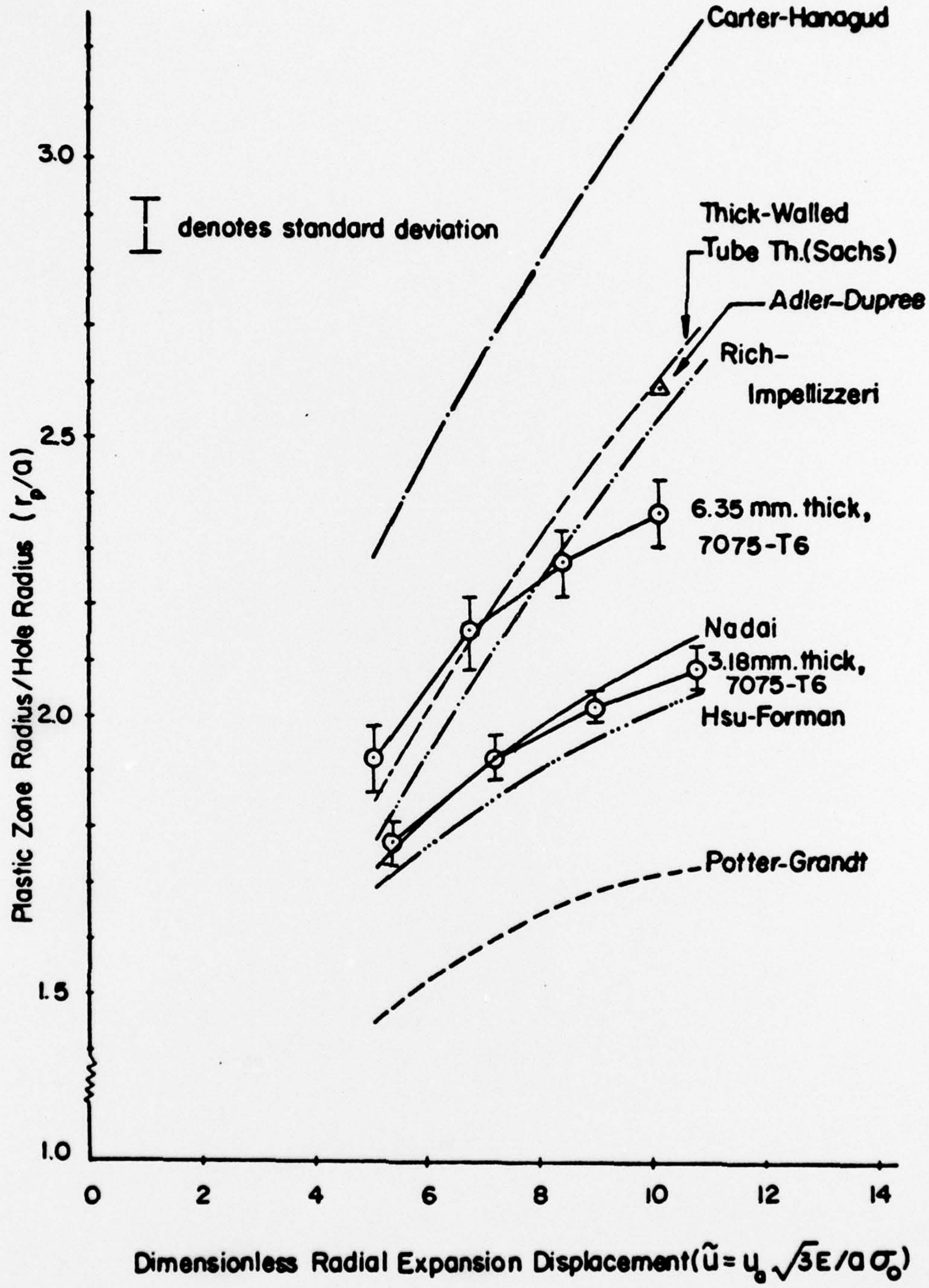

Figure 4 --Comparison of the elastic-plastic boundaries predicted by various theories and experiments for 7075-T6 aluminum.

tests of coldworked fastener holes also show that increasing the amount of expansion does not increase the life proportionately.

Plane-stress theories predict the location of the boundary adequately in thinner specimens. These theories are easy to use (particularly Nadai's) and could be readily incorporated into the design process.

When the hole diameter is the same as the specimen thickness, then plane strain theories are better--at least for small expansions. If one wished to have a conservative design criterion for hole spacing that was independent of thickness, the plane-strain theories would be best.

PART III -- CRACK INITIATION AND GROWTH

<u>References</u>--This phase of the research is reported in the Ph.D. thesis of:

Captain N. Chandawanich, Royal Thai Air Force, entitled "An Experimental Study of Crack Initiation and Growth from Coldworked Holes".

A paper with the same title by N. Chandawanich and W. N. Sharpe, Jr. has been submitted to Engineering Fracture Mechanics. The work has been accepted for presentation at the annual S.E.S.A. meeting in May 1978.

<u>Summary</u>

The two main purposes of this work were to measure the initiation and growth of cracks (most parameter studies have recorded only the specimen life) and to compare measured stress intensity factors with those calculated by a linear elastic superposition technique.

Specimens of 7075-T6 aluminum with 5 mm diameter holes were cyclically loaded with a remote stress that produced a tangential stress (based on an elastic stress concentration factor) at the hole edge slightly above the material's elastic limit. The holes were either not coldworked at all, or coldworked to a 3.7 or 5.8 percent final expansion.

At this level of loading (slightly above the elastic limit at the hole edge), coldworking affects the growth-rate of radial cracks more than it does their initiation. Cracks appeared in all of the specimens after $\sim 10^4$ cycles, but coldworking extended the specimen life to $\sim 10^5$ cycles. There is an optimum level of coldworking, i.e., as one expands the hole more, life does not increase appreciably. This fact appears in the analysis by Potter and Grandt (27) and is important because in industrial coldworking one must be concerned with the force on the mandrel, the surface deformation, etc.

Strains were measured at the hole edge prior to initiation by the Moiré technique and used in the Smith, et al. (14) relation to predict initiation. The relation works well for the noncoldworked holes only. This implies that the stress state at the coldworked hole edge is not accurately predicted by the analysis or that coldworking produces damage that makes initiation easier. The strain increments during loading are approximately the same for both coldworked and noncoldworked holes, i.e., the main effect of coldworking is to lower the mean value of the applied cyclic stress.

Coldworked holes show large amounts of closure for short cracks which is consistent with the concept of residual compressive stresses produced by the operation. The crack surface displacement of the noncoldworked holes is adequately predicted by the conic representation of Orange (15). The shape of the cracks in the coldworked specimens is also described by his formula although the magnitude is different.

The completely analytical computation of the stress intensity factor by the Grandt (16) method agrees well with the experimental results for cracks longer than 1 mm in coldworked specimens. By "completely analytical," is meant the method outlined in his paper coupled with the residual stresses computed from the Hsu-Forman (3) paper. Figure 5 shows the comparison between measured and predicted stress intensity factors for a heavily coldworked hole.

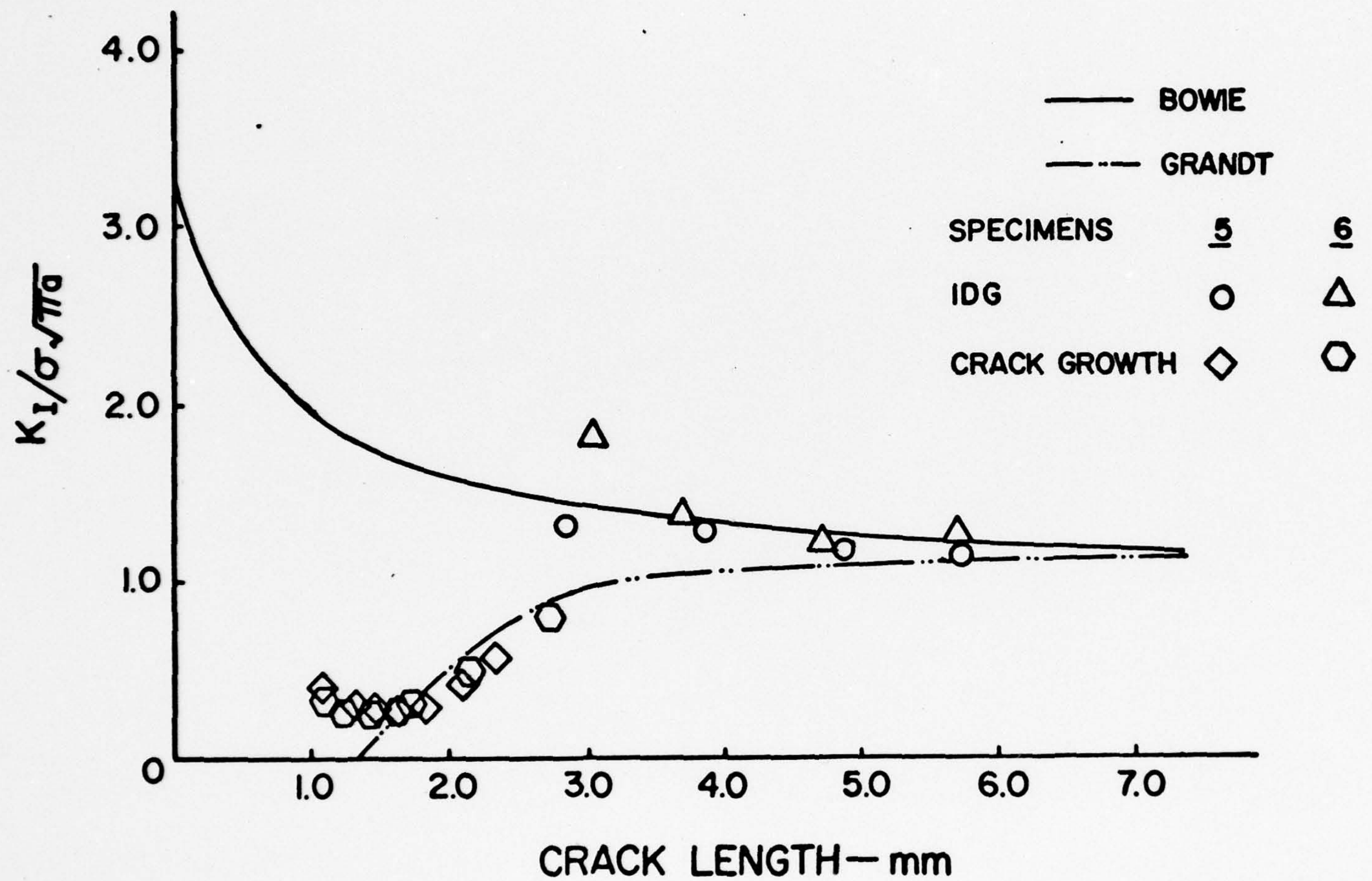

Figure 5. Comparison of the stress intensity factor predicted by Grandt with the measured values. The 6.6 mm hole in 7075-T6 aluminum was expanded 0.3 mm.

This work shows that a continuum mechanics analysis based on elastic behavior can adequately predict the stress intensity factors of cracks longer than 1 mm emanating from coldworking holes. It does not adequately predict the initiation of those cracks. Therefore it is more useful in predicting the behavior of cracks discovered by inspection than in predicting the entire life of a coldworked fastener hole.

PART IV -- COLDWORKING OF PRECRACKED HOLES

References--This phase is reported in the Master's thesis of: Walter Cesarz and in an AFOSR Scientific Report entitled, "Crack Growth from Fastener Holes Repaired by Coldworking".

Summary

This part of the research is similar to Part III except that the holes were precracked and then coldworked. Noncoldworked specimens were cyclically loaded until cracks approximately 1 mm long were detected. Then the hole was coldworked a medium amount ($\sim$ 3.7 percent expansion) and loading resumed.

The primary result was that this repair operation did indeed increase the life, but the results were less uniform. About half of the specimens failed before 100,000 cycles (compared to 25,000 cycles for a noncoldworked hole), and the other survived 400,000 cycles or broke outside the hole region. The specimens that lasted longest had several cracks around the hole.

PART V -- CONCLUDING REMARKS

The most significant and useful part of this research program has been the experimental evaluation of the strengths and weaknesses of the existing continuum mechanics theories of coldworked holes. In brief, for expansions that are large enough to produce appreciable increases in fatigue life, the theories do not predict the residual strains at the hole edge very accurately; however, they do a reasonable job of predicting the strains away from the hole and the location of the elastic-plastic interface. The main weaknesses of the theories are their treatment of the unloading behavior and omission of three-dimensional effects.

The coldworked hole is a tough problem, both theoretically and experimentally. Clearly plane stress is an inappropriate assumption near the hole edge, but dropping this assumption makes for a very difficult elastoplastic problem. The large strains and large gradients near the hole require tedious experimental mechanics techniques.

The linear elastic superposition method of Grandt, coupled with existing residual stress theories, predicts stress intensity factors in good agreement with measured ones for cracks longer than 1 mm. This is perhaps a bit suprising because of the nonlinear plastic deformation and inadequacies of the theories near the hole edge, but note this approach only works away from the edge. The continuum mechanics methods are not able to predict the initiation and short-crack growth of cracks from coldworked holes, but they are capable of predicting the behavior of longer cracks. In other words, they are more useful when applied to existing cracks discovered by inspection than in predicting the life-time of an initially coldworked structure.

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