UNIVERSITI PUTRA MALAYSIA

FINITE ELEMENT EVALUATION OF ELASTO-PLASTIC RESIDUAL STRESSES AROUND COLDWORKED FASTENER HOLES

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By

ABDALLA A. AB. RASHDI

Thesis Submitted in a Fulfilment of the Requirements for the Degree of Master of Science in the Faculty of Engineering Universiti Putra Malaysia

June 2000

Dedicated to my Parents, brother and sisters

And to my wife and kids Ali & Alla

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirements for the degree of Master of Science

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Chairperson: **Associate Professor Prithvi Raj Arora, Ph.D.**

Faculty: **Engineering**

The present work on the simulation of cold-working process using finite element analysis was devoted to two parts. The first part concerns with axisymmetric finite element analysis of elastic-plastic 2024-T351 aluminium alloy. The material was considered isotropic and a Von Mises yield stress criterion with hardening rule was assumed. The commercial finite element software, LUSAS-13.1, was used to simulate the cold-working process in a 6 mm thick plate with a 6.35 mm diameter hole with 4% radial expansion for three different models. The second part deals with the effect of support position along the exit face on the residual stress distribution around the hole. Finite element analysis of eight axisymmetric models with different support positions was considered

The finite element results for first part of the analysis showed that the radial residual stresses were of a compressive nature, except for a thin layer on the entrance face of the specimen. Models 1 and 2 gave a lesser spread of compressive tangential

residual stresses data than that obtained from model 3 The tangential residual stresses at the entrance face were tensile in nature while beyond 1 mm from the top surface through the rest of the thickness and along the edge of the hole they were compressive in nature The results were compared with previous results in the literature and good agreement was obtained

The analysis of the second part showed that the distribution of the tangential residual stresses at the exit face suggest the superiority of the support conditions 7 and 8 compared to support conditions 1 to 6 The magnitude of the spurt in value of the residual stresses varied with support condition and finally reduced to zero for support condition starting from 15 to 20 mm from the edge of the hole

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia
sebagai memenuhi keperluan untuk ijazah Master Sains.

PENILAIAN UNSUR TERHINGGA TERHADAP KETEGANGAN KEKAL ELASTO-PLASTIK DI SEKELILING LUBANG PENGUNCI YANG DIKERJA DINGINKAN

Oleh

ABDALLA A. AB. RASHDI

June 2000

Pengerusi : **Professor Madya Prithvi Raj Arora, Ph.D.**

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Penyelidikan ini melibatkan simulasi proses kerja-dingin menggunakan analisa unsur terhingga yang telah diusahakan kepada dua bahagian. Bahagian pertama adalah mengenai analisa unsur terhingga paksi simetri ke atas aloi aluminium 2024 T351. Bahan yang digunakan adalah isotropik dan Von Mises tegasan alah dengan peraturan kekerasan yang diambil kira. Perisian komersial unsur terhingga, LUSAS-13.1, digunakan untuk simulasi proses kerja-dingin pada plat yang berketebalan 6mm dan lubang berdiameter 6.35mm dengan 4% pengembangan jejari untuk tiga model yang berbeza. Bahagian kedua pula terlibat dengan kesan posisi sokongan disepanjang permukaan luaran pada taburan tegasan baki disekeliling lubang. Ini mengambil kira analisa unsur terhingga bagi lapan model paksi simetri dengan perbezaan posisi sokongan.

Keputusan unsur terhingga untuk bahagian pertama analisa menunjukkan taburan tegasan baki bersifat mampat, kecuali bagi lapisan nipis pada permukaan masukan spesimen. Model 1 dan 2 memberi data taburan tegasan baki yang merebak secara rambang berbanding model 3. Taburan tegasan baki pada permukaan masukan

adalah bersifat tegangan manakala ketebalan yang melebihi 1mm dari permukaan atas dan terus melalui ketebalannya, ia juga melalui tepi lubang dan bersifat mampat. Keputusan yang didapati adalah bersesuaian dengan keputusan yang sedia ada dalam kajian selidik

Analisa bahagian kedua menunjukkan taburan tegasan baki pada permukaan luaran mencadangkan keadaan sokongan 7 dan 8 yang lebih baik berbanding dengan keadaan sokongan 1 dan 6. Magnitud spurt dalam nilai tegasan baki berbeza-beza dengan keadaan sokongan dan akhirnya berkurang menjadi sifar untuk keadaan sokongan bermula dari 15 hingga 20 mm dari hujung lubang.

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I certify that an Examination Committee met on 13 Jun 2000 to conduct the final examination of Abdalla A Ab Rashdi on his Master of Science thesis entitled "Finite Element Evaluation of Elastic-Plastic Residual Stresses Around Coldworked Fastener Holes" in accordance with Universiti Pertanian Malaysia (Higher Degree) Act 1980 and Universiti Pertanian Malaysia (Higher Degree) Regulations 1981 The Committee recommends that the candidate be awarded the relevant degree Members of the Examination Committee are as follows

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DECLARATION

I hereby declare that the thesis is based on my original work except for quotations and citations, which have been duly acknowledged. I also declare that it has not been previously or concurrently submitted for any other degree at UPM or other institutions.

Name: Abdalla A. Ab. Rashdi

Date: 21. 6. 2000

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LIST OF ABBREVIATIONS

r_p	Plastic zone radius
r	Radius measured from the center of the hole
a	Radius of the hole
u_a	Radial displacement at $r = a$
E	Modulus of elasticity
v	Poisson's ratio
σ_r	Radial stress
σ_θ	Tangential stress
σ_y	Yield stress
G	Shear modulus of elasticity
b	Distance from the center of the hole to the edge of the plate
σ_o	Flow stress
n	strain hardening
p_i	Internal pressure
$\bar{\sigma}$	Equivalent stress defined by Von Mises yield criterion
${}^tT$	The current temperature
${}^tk$	State variable dependent upon equivalent plastic strain ${}^t\bar{e}^p$
λ	The Lagrangian plastic multiplier
Q	Plastic potential

k_0^c	Initial yield stresses in compression
k_0^t	Initial yield stresses in tension
H	The isotropic hardening tangent
H_α	The kinematic hardening tangent
α	The position in stress space of the center of the yield surface

CHAPTER 1

INTRODUCTION

Cold working fastener holes is a mechanical method of strengthening metallic components by retarding crack growth around the hole. The generic cold working process involves either pushing or pulling hardened mandrel through a fastener hole. The process expands the material around the hole, creating a radial plastic flow of material, thereby producing a high residual compressive stress zone around the hole. The residual stress zone, depending upon variables such as material and applied expansion levels, will extend approximately one radius from the edge of the hole for most of the practical situations. The zone acts as a barrier to crack growth, thereby increasing the fatigue life of the part.

1.1 Problem Statement

The current work is concerned with the finite element study to evaluate the residual stresses resulting from cold working of a hole. The LUSAS a commercially available finite element code is used to carry out a two dimensional axisymmetric elasto-plastic formulation to simulate cold working process. For this investigation a 6mm thick plate of 2024-T351 aluminum alloy with 6.35mm diameter hole. In order to verify the models, the results of the finite element analysis will be compared with the result of some pervious work from the literature. The second part of this investigation constitutes examining the effect of support position, along the exit face of the plate specimen, upon the residual stress field around the hole region.

1.2 Aim and Objectives

The following are the main objectives of the present study.

- To examine and investigate the residual stresses around cold worked fastener hole
- To examine the effects of support position along the exit face of the specimen upon the resulting two-dimensional axisymmetric residual stress field
- To optimise the developed model
- To verify the developed FE model with previous work from literature results

1.3 Thesis Layout

The thesis is divided into five chapters. Chapter 1 deals with introduction and the objectives of the research. Chapter 2 introduces the Literature review. Chapter 3 is concerned with the method of approach adopted in the present work. Chapter 4 consists of the finite element analysis results and discussion. Chapter 5 gives the Conclusions drawn from the present investigation.

CHAPTER 2

LITREATURE REVIEW

2.0 Introduction

Cold expansion of fastener holes has been used for over 40 years in the aerospace industry. It is a very efficient approach, which results in extending the fatigue life of the treated part without any weight penalty. Until recently, particularly for civil aircrafts, the technique was only applied to critical holes in the highly loaded zones of the structure, such as landing gears and engine mounting regions. In modern aircrafts, however, one may find over a thousand cold-expanded holes in the wing alone. The requirement of increasing structural efficiency combined with a reduction in manufacturing costs has demanded a closer study of the cold expansion process.

2.1 Description of Cold Working Process

The cold expansion of hole is usually conducted by pushing through an oversized ball or a mandrel Figure 2.1.1. The radial interference between the "rigid" ball or mandrel and the hole results in inhomogeneous plastic deformation. Upon unloading, the plastically stressed region, away from the hole, would tend to fully recover elastically resulting in compressive residual stress field. This highly localized compressive field at or near the hole boundary is equilibrated by the development of a tensile residual stress field in the surrounding regions. (Papanikos and Meguid, 1998) These compressive residual stresses are highly effective in preventing premature fatigue failure under conditions of cyclic loading A major impediment to the use of mandrel in the cold hole expansion of fasteners is the surface damage introduced at the interface during the cold expansion process To overcome this difficulty, the split sleeve expansion, split mandrel expansion methods have been developed (Leon, 1998) as shown ın Figure 2 1 2

In the split sleeve method, a thin, dry lubricated sleeve is placed over the stem of the mandrel and is pushed through the hole creating an interference fit The mandrel is then drawn back through the split sleeve Aircraft holes commonly treated by this method range from 5 mm to over 40 mm in diameter, with expansions between 2 and 6% depending on the material and application

There is no precise method for determining the optimum amount of cold expansion for any given application In split sleeve cold expansion, the selection of optimum amount of cold expansion rely on conducting a series of fatigue tests for several levels of cold expansion and thereby selection is made on the basis of improvement in fatigue life Typical improvements in the fatigue life of fastener holes that have been cold expanded are 3 1 or greater In the split mandrel method, the mandrel is pushed easily through the hole because of the presence of a machined groove along its length Thıs method was developed to replicate all the functions of the split sleeve technique and avoid the use of the sleeve The introduction of beneficial residual stresses by cold expansion, a widespread practice in many structural applications, requires in depth study of both analytical and experimental solutions Many analytical and experimental models have been developed in the area of cold expansion of fastener holes (Lınk and Sanford, 1990)

The analytical solutions can be divided into two-closed form solution and numerical (finite element solution). In most closed form solutions, the cold expansion is taken as an adaptation of the problem of a thick walled cylinder subjected to internal pressure. In the present work, the finite element solution is used to evaluate the residual stresses around cold worked fastener hole.

2.2 The Mechanics of Cold Expansion of Holes

Cold expansion of holes is a commonly adopted cold working method for fatigue life enhancement of plate specimen with a hole. The unloading residual stresses resulting from this cold working operation determine the fatigue life improvement of the structure. The mechanics behind cold expanding a fastener hole is shown graphically in Figure 2.2.1. The hole is untreated and contains the original residual stress, which can be in a state of compression or tension depending on the history of manufacture Figure 2.2.1a. When the mandrel is fully engaged hoop stresses will be tensile and can reach the yield stress of the alloy, Figure 2.2.1b. When the mandrel is removed from the expanded hole and in order to restore equilibrium conditions, the remaining elastic material causes a spring back, which generates compressive stress at the edge of the hole, Figure 2.2.1c. The distance of the plastic zone radius (r_p) and magnitude over which the compressive stresses extend depend on the degree of expansion. The radial stress will be zero initially but may become compressive with distance from the edge of the hole. Tangentially (in the hoop direction) the residual stresses are compressive over a certain distance from the hole, and then change to a tensile state of stress before becoming compressive again. Many investigations have been carried out using cold expansion process and thereby improve the fatigue life of the aerospace structural components. A brief outline is given here about numerical, analytical and experimental work in this area.

2.3. Finite Element Analysis

Until the advent of computers, the only way to find the answer to the engineering question, "what would happen if I did this to my new design?" was to build a prototype and carry out the necessary tests. Today computers allow designs to be assessed much more quickly and easily. Evaluating a complex engineering design by exact mathematical models, however, is not a simple process. Since we cannot calculate the response of a complex shape to any external loading, we must divide the complex shape into lots of smaller simple shapes or element. The coordinates of its nodes define the shape of each finite element. So that these elements are interconnected at specified points, which are called nodes. The real engineering problem responds in an infinite number of ways to external forces. The manner in which a particular finite element model will react depends on its degrees of freedom. Since we can express the response of a single finite element to a known stimulus we can build up a model for the whole structure by assembling all of the simple expressions into asset of simultaneous equations with degrees of freedom at each node as the unknowns. These are then solved using a matrix solution technique. For a mechanical analysis, once the displacements are known the strains and stresses can be calculated (LUSAS User Guide, 1995, and LUSAS Modeller User Manual, 1998).

Bernard, et al (1995) carried out an axisymmetric finite element analysis of cold expansion process, accounting for contact between the mandrel and the hole surface to assess the residual stress induced by re-cold working process The first cold work was of 5 58 % and the subsequent one in the backward direction was of 4 8 % The direction of the second cold working determines on which face will be the more compressive residual stress At the hole edge, the entry face is presently subjected to a larger compressive residual stress than at the exit face, this situation is opposite to the case of a single cold working Figure 2 3 1 When the second cold working is performed in the forward direction, the resulting residual stress field is essentially comparable to that induced by a backward coldworking as shown in Figure 2 3 2 This indicates that the direction of the mandrel movement during the second coldworking has practically no influence on the mid-thickness residual stresses They found that the second coldworking may enhance the fatigue life of an already coldworked hole Figure 2 3 3

A two-dimensional finite element analysis under plane strain, plane stress and axisymmetric condition was carried out by Poussad et al, (1995) to simulate 4 per cent cold working of thick plate of 2024-T351 aluminum alloy The simulations were used to assess the influence of strain hardening, the role of reversed yielding and through-thickness residual stress distributions, using ABAQUS and ANSYS finite element codes Both isotropic and kinematic strain hardening models were used to evaluate the influence of Baushchinger effect The results show that smaller compressive residual stresses were obtained using kinematic hardening Figure 2 3 4 An axisymmetric finite element model of the cold working process revealed that there were nonuniform residual stress distributions through the plate thickness Figure 2 3 4

Pavier, et al , (1997) conducted two-dimensional axisymmetric finite element simulations for the cold working of a fastener hole in an aluminum plate using the ABAQUS finite element code to evaluate the radial and tangential residual stresses They have compared the simulation results with a simplified finite element model where the cold working process is reduced to applying a uniform radial expansion to the hole edge It is shown that substantial differences exist between the finite element simulations, specially, the simulation of the actual process shows tensile residual radial stresses on the surface of the plate after cold working whereas the simplified uniform radial expansion shows only compressive ones Figure 2 3 5

Papanikos and Meguid (1997) used ANSYS finite element code to model simulation of the residual stress field resulting from the cold expansion of two adjacent fastener holes, the development and growth of the plastic zone and unloading residual stresses were examined Their results have shown that increasing the expansion level results ın a reduction in the tensile field, leading to a purely compressive residual stress field at an expansion level of 6% Figure 2 3 6 The center distance between the two holes influences the residual stress field Sequential expansion leads to higher tensile residual stress than simultaneous expansion Figure 2 3 7

Smith et al, (1998) measured residual stress distribution resulting from cold working process using Sachs method The measured results are in good agreement with averaged through thickness predictions of residual stresses from an axisymmetric finite element model of the cold working simulation process Figure 2.

residual stresses found from finite element model of the working process.

Pavier et al., (1998) conducted three-dimensional finite element simulation to predict the residual stress distribution for cold working of a fastener hole in aluminum plate. Following the cold working simulation, unidirectional tensile mechanical load is applied to the plate and the resulting redistribution of stress in the specimen was evaluated. Predicted cracks emanating from the hole are then introduced into the model and crack opening displacements and stress intensity factors are predicted along the crack front as a function of mechanical loading. The present results were compared with the results of axisymmetric simulation. The finite element simulation shows that cold working has beneficial effects represented by reduction the stress intensity factors under applied mechanical load compared to a non-cold worked plate. The axisymmetric simulation is able to predict higher peak values of residual stress than the three-dimensional model at the exit face Figure 2.3.9, these stresses have little effect on the subsequent loading and fracture behaviour on the plate, as the cracks initiate from the entrance, not from the exit face.

Papanikos and Meguid, (1998) conducted three-dimensional elasto-Plastic finite element analysis to evaluate the development and growth of the plastic zone and unloading residual stresses resulting from the cold expansion of two adjacent holes. Both simultaneous and sequential expansion of the two holes was considered. Their results indicate that the improper cold expansion of adjacent holes can lead to high tensile residual stresses. The center distance between the expanded holes influence the compressive residual stresses at the entry face of the work piece Figure 2.3.10. The sequential expansion results in lower compressive residual stresses than the simultaneous expansion especially at the exit face of the specimen as shown in Figure 2.3.11.

2.4 Analytical Investigations

The most prominent theories about the cold working are summarized in this section. They cover the spectrum of elastic-plastic analysis and are a good example of the historical development of plasticity theory.

Nadai Theory:

Nadai, (1943) developed a theory of plastic expansion of small tubes fitted into boiler heads. He considered the plastic deformation of both the plate and tube.
His assumptions were

i) Uniform pressure at the inside edge of the hole in infinite plate.
ii) Von Mises-Hencky yield criterion.
iii) Perfectly plastic material response.

He has developed a relationship to estimate the radius of the elastic-plastic boundary, "The ellipse of plasticity", which led to a maximum value of $r_p = 1.75a$. A linear approximation to the Mises-Hencky yield criterion was assumed. He developed the following equations