Elastic-Plastic Behavior of Coldworked Holes

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The objective of this paper is to describe a four-stage analytical procedure used to determine the crack-growth response for coldworked open holes, and holes filled with neat- and interference-fit fasteners. The methodology utilizes an elastic-plastic finite element analysis program to determine residual stress states. A crack-growth procedure, modified to include the residual stresses, is used to evaluate the coldworking process. Consideration is given to the effects of various degrees of coldworking, interference levels, short-edge margins, and magnitudes of compressive overloads on the residual stresses. For those conditions involving compressive overloads applied to coldworked neat- and interference-fit fasteners, further consideration is given to the effects of slip vs no-slip conditions at the fastener-sheet interface. A comparison of results between analysis and test data is presented for the crack-growth response of coldworked open-hole specimens.

Nomenclature

c	= crack length
D	= diameter of hole prior to coldworking
$\bar{D}$	= expanded diameter of hole
D_R	= residual diameter of hole (after coldworking)
D^*	= diameter of fastener
e	= edge distance from hole center
E^*	= material constant, Eq. (2)
$\{F\}$	= vector of constraint forces, Eq. (4)
i	= measure of coldwork (percentage), Eq. (3)
$[K]$, $[\bar{K}]$	= stiffness matrices, Eqs. (4) and (5), respectively
K, K_∞, K_R	= stress intensity factors, Eqs. (1) and (2)
$p(x)$	= residual stress distribution, Eq. (2)
$\{P\}$	= vector of forces for remote loads, Eq. (7)
$\{Q\}$, $\{\bar{Q}\}$	= plastic residual load vector, Eqs. (4) and (5), respectively
R	= stress ratio (min/max)
$\{u\}$	= vector of independent nodal displacements, Eq. (4)
$\{u_R\}$	= vector of residual nodal displacements, Eq. (5)
x	= distance along crackline, Eq. (2)
ΔK	= range of stress intensity
$\eta(x)$	= displacement profile along crack surface, Eq. (2)
ξ	= distance from edge of hole in x direction

Introduction

THE coldworking of a hole in a wide sheet is analogous to the process of shrink-fit or autofrettage of laminated circular tubes. Beneficial compressive residual stresses are developed upon inserting an oversized tapered mandrel through the hole and then allowing the hole to spring back from its expanded position to a residual deformation state. To prevent damage to the hole, a sleeve (full or split) generally is placed between the hole and mandrel during the coldworking operation. The compressive residual stresses extend radially from the edge of the hole for some finite distance, and significantly contribute to retarding crack initiation and crack growth. Consequently, there have been numerous investigations[1-10] focused on the effectiveness of the coldworking process to inhibit crack initiation and crack growth for open holes as well as for holes with neat- and interference-fit fasteners.

A significant number of previous investigations associated with determining residual stresses from a coldworking process utilize closed-form solutions for a concentric thick tube[11] or for a hole in an infinitely wide sheet.[12] These solutions are restricted to axisymmetric situations and for materials exhibiting elastic/ideally-plastic behavior. Neither of these restrictions are necessary in the analytical formulation of this investigation.

In the present paper, a review is presented of some of the pertinent literature associated with determining the fatigue life characteristics of coldworked holes. This review is followed by a description of a four-stage analytical procedure that can be used to determine the crack-growth behavior of an initial flaw emanating from the edge of a coldworked hole. At the core of this analytical procedure is an elastic-plastic finite element analysis program capable of tracking the path-dependent process of coldworking, introducing an interference-fit faster, and determining the effects of subsequent remote loads on the residual stress state. These residual stresses are then used in a crack-growth analysis program to establish life to unstable growth.

The analytical methodology is capable of treating four factors that can significantly effect the residual stresses: 1) various levels of coldworking in the coldworking process, 2) hole condition (open hole vs holes with neat- and interference-fit fasteners), 3) short-edge margins, and 4) compressive far-field loads.

For those conditions involving compressive overloads applied to coldworked interference-fit holes, further consideration is given to the influence of slip conditions at the fastener-sheet interface. Analytical results are presented for a number of situations involving a single sheet material and hole diameter. A comparison of results between analysis and some limited test data is presented for the crack-growth response of a coldworked open-hole specimen subjected to an airplane fuselage load spectrum.

Background

An experimental study designed to evaluate the effectiveness of various parameters to improve the fatigue life of coldworked holes is presented by Phillips.[1] In this study, three materials (aluminum, titanium, and steel) are considered for coldworked open holes, and neat- and interference-fit fasteners. One particularly pertinent conclusion reached in this investigation is that edge margins and hole spacing variations result in no appreciable degradations in fatigue performance for coldworked holes with edge margin ratios (edge distance to hole diameter) as low as 1.5, and hole spacing as small as 3 diameters.

Based on a number of tests conducted on aluminum, titanium, and steel specimens, Hall et al.[2] established the

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improvement in fatigue crack propagation life of cracked fastener holes through the use of interference-fit fasteners or coldworking procedures. From an analytic viewpoint they conclude that crack-growth life for cracks originating at conventional close-tolerance holes can be determined accurately for situations involving circular part-through cracks with simple loadings and low load transfer.

Petrak and Stewart[3] evaluated the effectiveness of a limited number of cold expansion open holes and interference-fit fastener systems to retard the growth of cracks emanating from precracked fastener holes. Constant amplitude loading with a load ratio $R=0.5$ (S_{min}/S_{max}) is treated, together with cases involving load transfer through the fastener. The results indicate that all of the fastener systems considered caused some degree of retardation.

The analytical and experimental results from Crews' investigations[4,5] verify the beneficial effects obtained with the use of interference-fit bolts. In his studies, Crews has demonstrated that the beneficial results are caused by compressive interference stresses in the sheet, and load transfer through the bolt. If clearance-fit bolts are replaced by interference-fit bolts, these beneficial effects result in a significant increase in life for constant-amplitude loading. The magnitude of the beneficial effects depend upon the level of interference as well as the bolt-to-sheet stiffness ratio. Crews determined that progressively higher interference levels prevent slipping (and thereby fretting) along the bolt-sheet interface, and consequently result in improved fatigue life. He also found that little additional improvement is achieved by increasing the interference level beyond that necessary to prevent slip for the maximum applied remote tensile loading. These results raise the possibility of defining an "optimum" interference level as that level corresponding to the enforcement of no-slip along the bolt-sheet interface.

While Crews' investigations are concerned with interference-fit fasteners and crack initiation, Chang[6] has focused attention on the crack-growth behavior at coldworked fastener holes. In the combined analytical-experimental investigation by Chang,[6] the residual stresses around a coldworked hole are approximated using a closed-form solution[11] to an elastic/ideally-plastic thick-tube problem, assuming elastic unloading. Good correlation for crack-growth behavior between analytical results and experimental data is presented for the case of two radial cracks growing from a 0.5-in.-diam open hole in a relatively wide ($e/D=4$) aluminum sheet.

In the investigation by Sha et al.[7] an elastic-plastic finite element analysis is used to determine the magnitude and distribution of residual stresses due to the radial expansion of a centrally located hole in long rectangular titanium specimens. The analysis is further used to obtain the residual stresses remaining after the application and subsequent removal of a far-field tensile load for an open-hole configuration. A qualitative assessment of the effects of various coldworking levels on the fatigue life has been carried out by comparison with experimental data for corresponding coldworked open-hole specimens. The analysis and experimental data indicate that there exists an optimum coldworking level beyond which the maximum compressive residual stress does not change in magnitude at the hole boundary. The compressive zone is shifted progressively from the hole perimeter with increasing levels of coldworking.

Another comprehensive analytical and experimental program to evaluate the fatigue behavior of coldworked and interference-fit fastener holes is presented by Rich and Impellizzeri.[8] In this study, approximate closed-form solutions are developed to define the residual stresses surrounding coldworked holes and interference-fit fasteners. These solutions are developed from an elastic/ideally-plastic analysis of thick-walled tubes subjected to uniform internal pressure,[11] and a closed-form solution to the problem of stress fields surrounding cylindrical inclusions. Slip con-

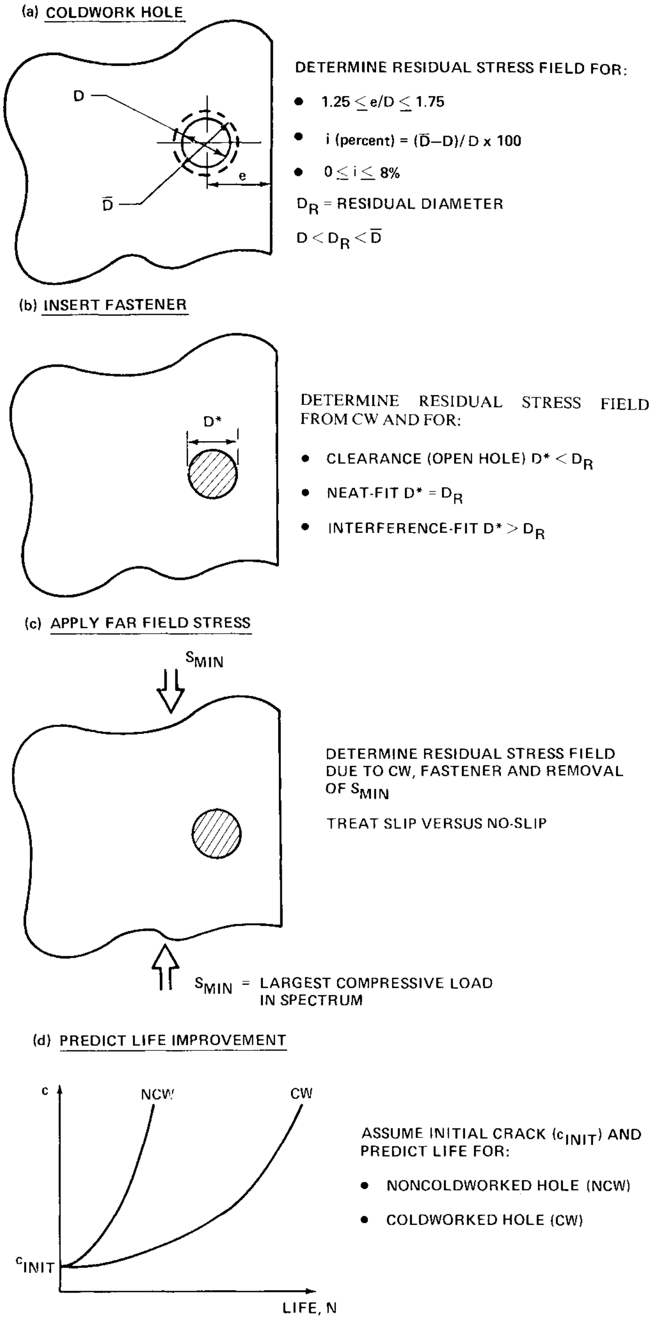


Fig. 1 Sequence of analyses.

ditions (zero shear continuity) are assumed along the bolt-fastener interface. Life predictions are made on the basis of a two-stage approach that includes crack initiation and crack growth to failure. Crack-initiation predictions are based on a cumulative damage model that accounts for prior load history and uses an equivalent strain amplitude to account for stress ratio (R values) effects. Stress intensity factors used to determine the crack growth of the specimens subjected to arbitrary spectrum loads are calculated by using a linear elastic fracture mechanics superposition procedure proposed by Grandt.[13] In this procedure, an effective stress intensity factor is used, and expressed as the sum

$$K=K_{\infty}+K_R \tag{1}$$

where K_{∞} is the stress intensity caused by loading in the absence of residual stresses, and K_R the residual stress intensity.

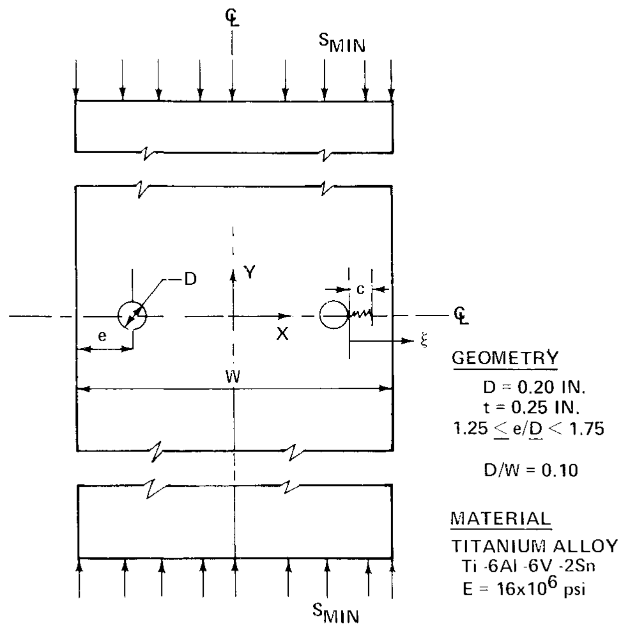


Fig. 2 Short-edge hole configuration.

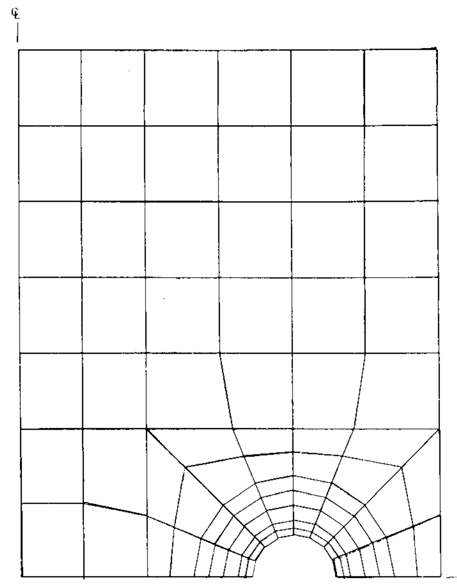


Fig. 3 Finite-element idealization of a quadrant of short-edge hole problem.

The residual stress intensity values are determined by a weight function method[14,15] from the general expression

$$K_R = \frac{E^*}{K_\infty} \int_0^c p(x) \frac{\partial \eta(x)}{\partial c} \, \mathrm{d}x \tag{2}$$

where K_∞ is the known stess intensity factor (flawed structure) for a prescribed remote loading.

Good correlation is achieved by Rich and Impellizzeri[8] between analysis and test results obtained for spectrum crack growth of open coldworked holes and coldworked holes with interference-fit fasteners in aluminum and titanium specimens. This correlation is particularly significant since it provides some justification for the use of Eq. (1) for treating the presence of residual stresses in crack-growth problems. Further justification for using this superposition procedure is provided by Chandawanich[9] and Cathey and Grandt.[10]

In summary, there are a number of studies associated with the coldworking process. With respect to analyses, all of these investigations generally consider the coldworking process as an axisymmetric problem in which the residual stresses are determined by using idealized solutions[11,16] or finite element methods.[4,5,17] The subsequent plastic deformation and changing residual stress fields around a coldworked hole, resulting from the application of far-field stresses, are treated in a limited number of investigations. In addition, fatigue life is treated as life to crack initiation, or as crack growth to failure from some initial crack size. In rare instances fatigue life is treated as a two-stage process accounting for both crack initiation and crack growth.

Description of Analyses

The sequence of analyses considered in the present paper is illustrated schematically in Fig. 1 as a four-stage procedure. Initially the coldworking process is treated by means of an elastic-plastic finite element method[18] for a variety of relatively small edge distance-to-hole diameter ratios. Note that the problem is not axisymmetric. Nevertheless, a residual diameter, D_R, is defined as that corresponding to the configuration of the hole upon unloading from some prescribed coldworking level (defined by i in Fig. 1). The preceding analysis determines the level and distribution of the residual stresses resulting from the coldworking process, and is followed by an analysis that considers the hole condition prior to the application of the remote stresses. The hole condition is a function of the size of the diameter of the fastener to be inserted into the coldworked hole (D^* in Fig. 1) relative to D_R. As seen from Fig. 1, clearance, neat- and interference-fit fasteners are considered. The coldworked residual stresses determined in Fig. 1a are affected by the introduction of the interference-fit fastener. Opening the hole to $D^* > D_R$ may be purely elastic, or may involve additional plastic deformation.

In Fig. 1c, a far-field stress corresponding the largest compressive stress in a prescribed spectrum is applied. For sufficiently large remote stress levels this loading will cause additional plasticity to develop around the bolt-sheet interface. For remote compressive loads, the resulting residual compressive circumferential stresses will be lowered, thus reducing the benefits of the initial coldworking process. In this stage, consideration is given to slip and no-slip conditions at the bolt-sheet interface. Furthermore, the level of applied remote stresses considered in this paper precludes consideration of separation between the bolt and sheet.

In Fig. 1d, the residual stresses determined from Figs. 1a-c are used together with an applied load spectrum to compare the crack-growth behavior of coldworked holes to that of noncoldworked holes subjected to the same spectrum. A brief description of the methodology associated with each analysis stage shown in Fig. 1 follows.

Coldworking

Coldworking is treated by means of a two-dimensional elastic-plastic finite element analysis[18] program in which an incremental solution algorithm based on the residual force method[19] is used. The hole expansion process is simulated by enforcing appropriate constraint conditions for those nodes on the hole geometry, and prescribing that the hole expand radially in a uniform manner to a diameter D corresponding to an initial expansion given by

$$i(\text{percent}) = \frac{\bar{D} - D}{D} \times 100 \tag{3}$$

where D and $\bar{D}$ are the original and expanded hole diameters, respectively.

At this point the sheet has experienced elastic-deformation and its behavior is governed by the following equilibrium

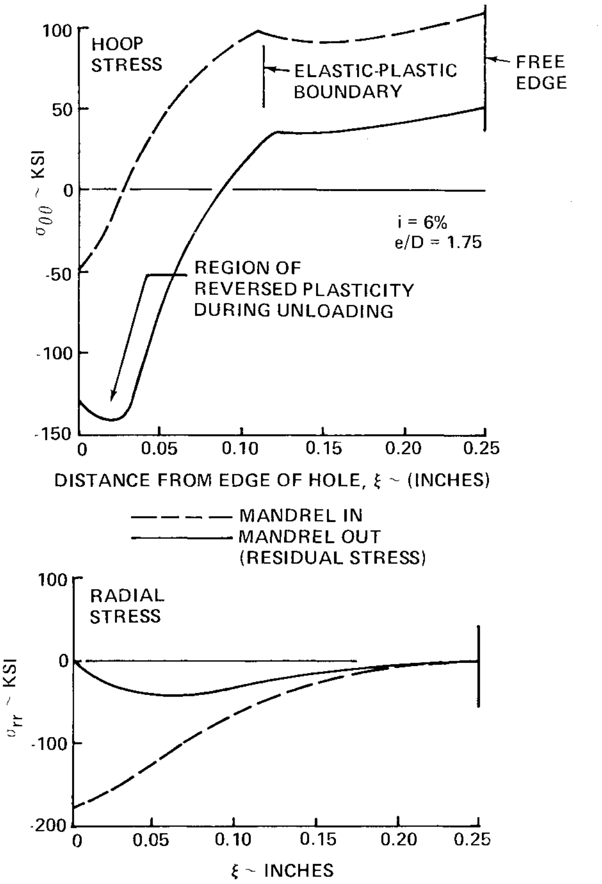


Fig. 4 **Stresses during coldworking.**

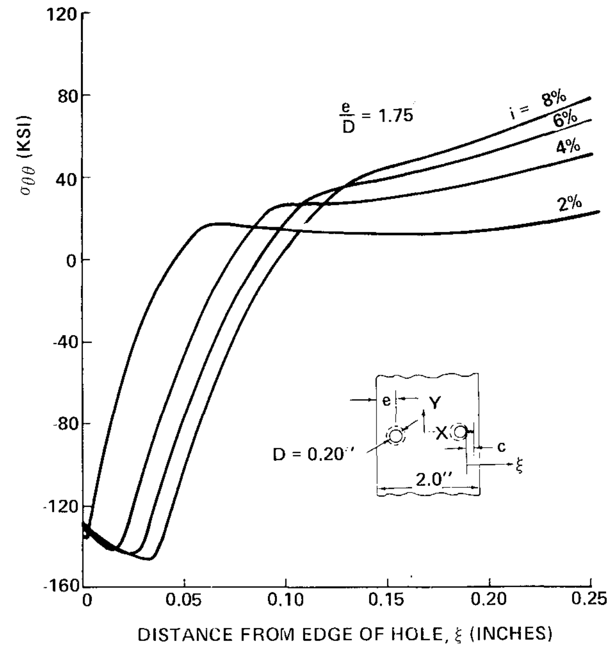


Fig. 5 **Residual stresses due to coldworking.**

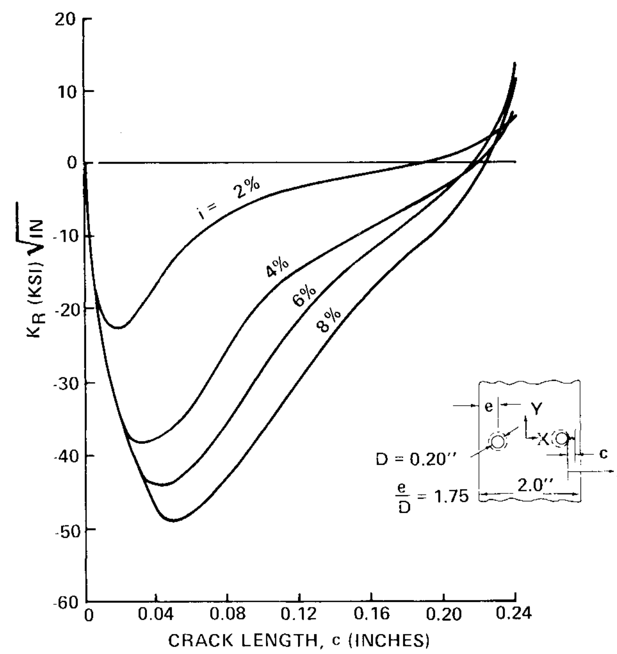


Fig. 6 **Residual stress intensity factor (effect of varying radial expansion).**

equation written in matrix form

$$[K]\{u\} = \{F\} + \{Q\} \tag{4}$$

It should be noted that $\{F\}$ does not generally represent a set of forces corresponding to a uniform radial pressure. It is determined from the applied displacements (including the constraint condition to ensure uniform radial expansion) and reflects the asymmetric character of the stiffness for the short-edge distance problem. The vector $\{Q\}$ is the set of nodal forces developed from prevailing plastic strains present in the structure. The plastic strains are treated as initial (lack-of-fit, thermal, etc.) strains.

The residual stresses corresponding to a spring-back from the cold expansion are determined by removing the multipoint constraint conditions previously imposed during the radial expansion of the hole. Accordingly, Eq. (4) becomes

$$[\bar{K}]\{u_R\} = \{\bar{Q}\} \tag{5}$$

where the elastic stiffness matrix $[\bar{K}]$ and plastic residual load vector $\{\bar{Q}\}$ differ from $[K]$ and $[Q]$ in Eq. (4) to account for the additional independent nodal degrees of freedom resulting from the release of the multipoint constraints. The vector of residual displacements $\{u_R\}$ is then used to establish corresponding levels of residual stresses and strains.

Type of Fastener

The hole condition prior to the application of the remote stresses can be one of three cases depending on the diameter of the fastener D^* relative to the residual diameter D_R. These possibilities include: 1) Clearance-fit (or open-hole), $D^* < D_R$; 2) neat fit, $D^* = D_R$; and 3) interference fit, $D^* > D_R$.

The first two possibilities will not alter the residual stress field developed from the cold working operation. The last possibility requires the reintroduction of the multipoint constraint conditions and the subsequent uniform radial expansion of the hole to a diameter D^*. This process may be elastic, or may result in further plastic deformation of the sheet. The reintroduction of the multipoint constraint conditions is equivalent to assuming a rigid bolt. The governing equations are identical to Eq. (4) with the vector $\{F\}$ appropriately scaled to provide the forces necessary to expand the hole to a diameter D^*.

Application of Remote Stresses

Two significant factors are to be considered for this stage of the analysis. The first is associated with the hole condition used in Fig. 1b; the second factor is concerned with the condition of slip vs no-slip along the bolt-sheet interface.

With respect to the first factor, appropriate multipoint constraints are enforced for the clearance, neat-, and interference-fit fasteners (a rigid pin assumption for all cases). These cases require that the interface boundary between the fastener and the sheet be monitored to avoid overlapping and allow separation. The open-hole case does not require enforcement of any constraint conditions along the interface.

The second factor to be considered is associated with the slip vs no-slip conditions. These conditions are treated by prescribing the circumferential degrees of freedom of those nodes on the bolt-sheet interface to be fixed (no-slip) or free (slip). The assumption of no-slip may be checked by comparing the ratio of the interface shear stresses $\tau_{r\theta}$ to radial stresses σ_{rr} along the interface. The appropriate conditions are

$$\tau_{r\theta}/\sigma^*_{rr} < \mu \text{ no slip} \quad > \mu \text{ slip} \tag{6}$$

where μ is the coefficient of friction between the fastener and sheet.

The elastic-plastic analysis procedure is similar to that of Fig. 1a with the governing equation now written as

$$[K]\{u\} = \{F\} + \{Q\} + \{P\} \tag{7}$$

where the stiffness matrix $[K]$ and load vector $\{F\}$ reflect the presence of constraint conditions, as well as conditions associated with slipping along the bolt-sheet interface. The vector $\{Q\}$ reflects the degree of plasticity developed through Figs. 1a-c, and the vector $\{P\}$ represents the loading for the remote applied stresses. The residual strains and stresses developed at this stage of the analysis are determined from the displacements remaining upon the application and subsequent removal of the remote applied load vector $\{P\}$.

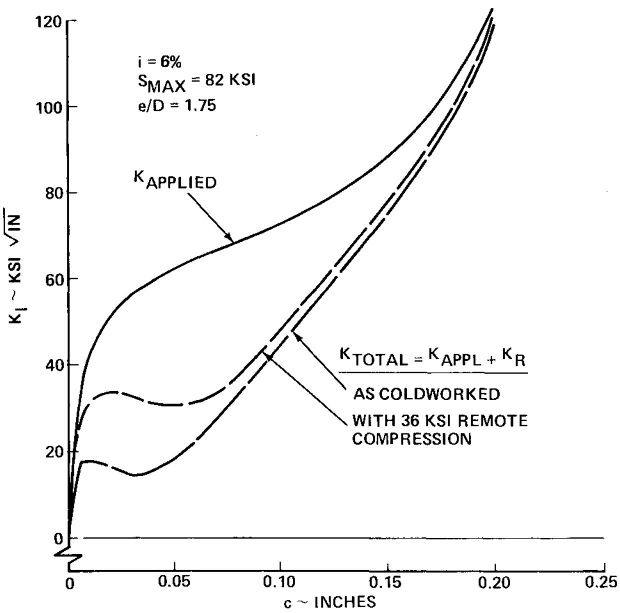


Fig. 7 Stress intensity factor, coldworked hole.

Crack-Growth Analysis

Crack growth predictions were made with a rate equation of the following form (developed by Bell and Creager[20]), which is based on the crack-closure concept.

$$\frac{dc}{dN} = C'\left[\frac{(1-C_f)}{(1-R)}\Delta K\right]^n \tag{8}$$

where C' and n are empirical constants and $C_f = C_f(R)$ is the closure factor.[20]

This equation describes crack-growth rate behavior as a function of stress ratio R. The empirical constants are determined by correlating crack-growth rate test data with a series of parallel, straight lines on a plot of log dc/dN vs log ΔK. Spectrum crack-growth analysis is performed by using the stress intensity range, ΔK, for each cycle in the randomized flight-by-flight spectrum. The stress intensities, K_{max} and K_{min}, were calculated by superposition of the applied and residual stress intensity factors as described by Eq. (1). Thus,

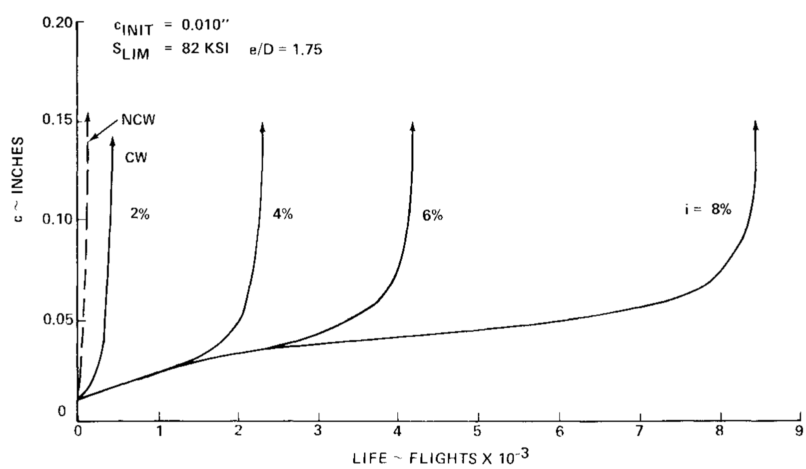
$$K_{max} = K^{applied}_{max} + K_R \tag{9a}$$

$$K_{min} = K^{applied}_{min} + K_R \tag{9b}$$

The residual stress intensity factors are calculated by the weight function technique [see Eq. (2)] using the residual stresses determined by the elastic-plastic finite element analysis for the uncracked structure. Here, a weight function developed for a crack at a concentric hole in a finite width plate was used to calculate K_R; for computational purposes, the width was taken as twice the edge distance ($e/D = 2$). Although the geometry for the weight function employed is somewhat different than the geometry analyzed, the error introduced is believed to be small. This same procedure was followed by Rich and Impellizzeri[8] with reasonable success. Crack growth was calculated by linear summation on a cycle-by-cycle basis.

Crack-growth interaction effects were predicted using a multiparameter yield zone (MPYZ) model[21] that utilizes Eq. (8). This model has been used to correlate many randomized flight-by-flight fatigue spectrum crack-growth tests and has proved to be reasonably accurate. The model uses an effective stress approach, similar to the Willenborg[22] model, but

Fig. 8 Effect of amount of coldworking on fatigue crack growth life (Ti-6Al-6V-2Sn through crack).



predicts more load interaction effects, including: 1) crack-growth retardation during load cycles following overloads, 2) crack-growth acceleration during the application of overloads, and 3) acceleration during load cycles following underloads and compression loads.

Analytical Results

The analytical methodology illustrated in Fig. 1, and described in the preceding paragraphs, was applied to the short edge distance-to-hole diameter configuration shown in Fig. 2. The geometry is representative of an airplane fuselage frame, having fastener holes located in close proximity to free edges. This detail is typical of many airframe structural components. The holes have a 0.20 in. diameter and a short edge distance e that is nominally 0.35 in. The material is 0.25-in.-thick titanium alloy, Ti-6Al-6V-2Sn mil-annealed plate, having a yield strength of 150 ksi. The results presented here are confined to the improvements in crack-growth life.

An elastic-plastic finite element analysis (FEA) was employed to calculate stresses produced by the coldworking process. The two-dimensional finite element model presented in Fig. 3 corresponds to the case of $e/D = 1.75$. However, this grid pattern and degree of refinement is typical for all cases considered. An automatic mesh-generating scheme that successively refines geometrically similar grid patterns is used to establish these grids. For each e/D ratio, the grid selected is one for which the elastic stress concentration factor at the edge of the hole in the short-edge ligament segment compares to within 3% of tabulated results[23] for the case of a uniformly distributed far-field load. This degree of refinement, combined with the use of an algorithm used to monitor and insure that the assumptions associated with the incremental plasticity theory are not being violated,[18] provide sufficient confidence in establishing the accuracy and convergence of our finite element solutions.

Of major concern in our analysis is the circumferential residual stresses (see Fig. 2) along the x axis in the ligament between the hole and the free edge, as it is expected that fatigue cracks will initiate here. The residual stress normal to the crack path along the x axis is used to compute the residual stress intensity factor, K_R, which in turn is employed in Eq. (1) to predict crack growth.

An elastic-plastic stress analysis of the coldworking procedure for a mandrel interference of 6% is presented in Fig. 4. The circumferential and radial stress distributions along the x axis are shown in the ligament starting at the edge of the hole and extending to the free edge. It is noted that after the mandrel is removed a region of large compressive hoop stresses appears adjacent to the hole. These compressive stresses retard the growth of fatigue cracks that initiate at the hole.

The effect of varying mandrel interference on residual stress and crack-growth life was investigated. Residual hoop stresses for interferences i ranging from 2 to 8% are calculated and are presented for the short-edged ligament in Fig. 5, where it is seen that increasing the interference level increases the region of large compressive stresses adjacent to the hole. However, the maximum compression stress level remains relatively constant, as it is limited by the compressive yield stress of the material. Also noted in Fig. 5 is an increase in magnitude of the residual tensile stresses near the free edge of the short ligament as the level of mandrel interference increases. Unlike the case for large e/D values, the short-edge ligament can provide sites (at the free edge) for potential stress corrosion cracks (SCC) to initiate and should be considered when selecting a mandrel interference level.

The calculated residual stresses, as a function of mandrel interference, were used with the weight function relation of Eq. (2) to predict residual stress intensity factors, K_R, and the results are presented in Fig. 6. It is noted that values of K_R are negative near the hole. These values will reduce the effective stress intensity factors, the mean stress of a given cyclic loading, and hence the crack-growth rates. A 6% nominal mandrel interference level was selected for the present study.

The configuration in Fig. 2 was subjected to a remote gross limit stress of 82 ksi. Combining the applied stress intensity factor with the K_R for an interference level of 6% results in a

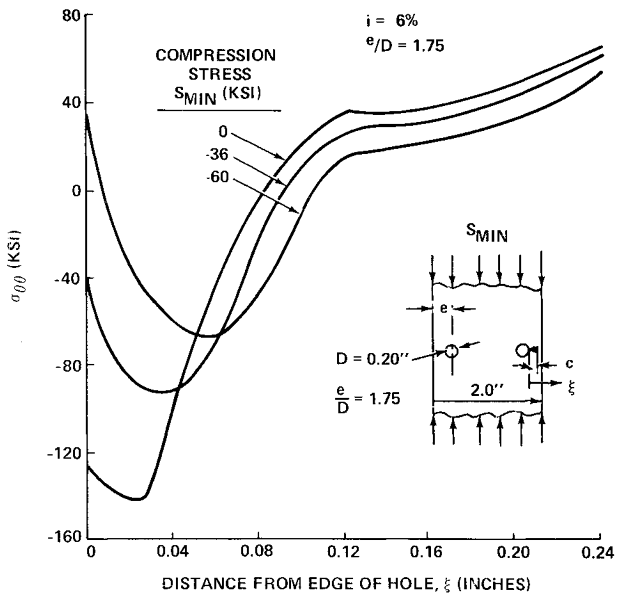


Fig. 9 Effect of compression load on residual stress due to coldworking (open hole).

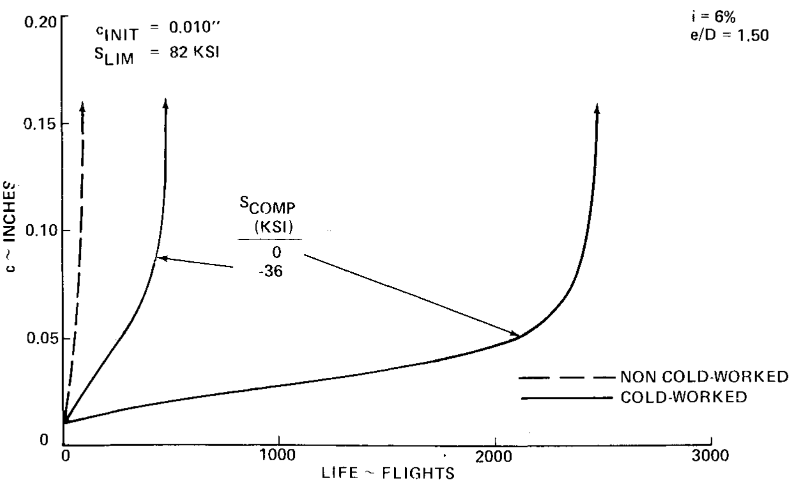


Fig. 10 Effect of compression on crack-growth life (open hole).

reduction in maximum stress intensity factor (K factor) as shown in Fig. 7. The K_R factor is also combined with the minimum K factors for a load cycle, resulting in an effective stress intensity factor range, ΔK, that is identical to that for the cycle without residual stress, but with a lower cyclic mean stress. It is the reduced mean stress that causes the crack-growth analysis to predict longer crack growth life. This configuration was then subjected to a randomized flight-by-flight ($F \times F$) fatigue load spectrum developed for a fuselage frame. This spectrum has a repeatable 440 flight block, a maximum load equal to limit load and a minimum load equal to -43% of limit load, or -36 ksi.

Predicted crack-growth lives for the various mandrel interference levels are presented in Fig. 8 where it is seen that the crack-growth life is greatly increased for interferences greater than 4%. This predicted increase in life varies by factors of 3-50, and indeed, is very sensitive to the interference level.

The effect of the largest applied compression load on the residual stress distribution is not present in the results of Fig. 8. For the present case, the maximum applied compression load is 36 ksi. The FEA was used again to calculate the effect of applying the 36 ksi remote compression stress on the "as-coldworked" configuration. As shown in Fig. 9, the compression load significantly reduces the compressive residual hoop stress near the edge of the hole. These results were used to compute new K_R values and crack-growth predictions, with the latter presented in Fig. 10. Here, the addition of the applied remote compression reduces the crack-growth life by a factor of 5 when compared to the case where the compressive load is not applied.

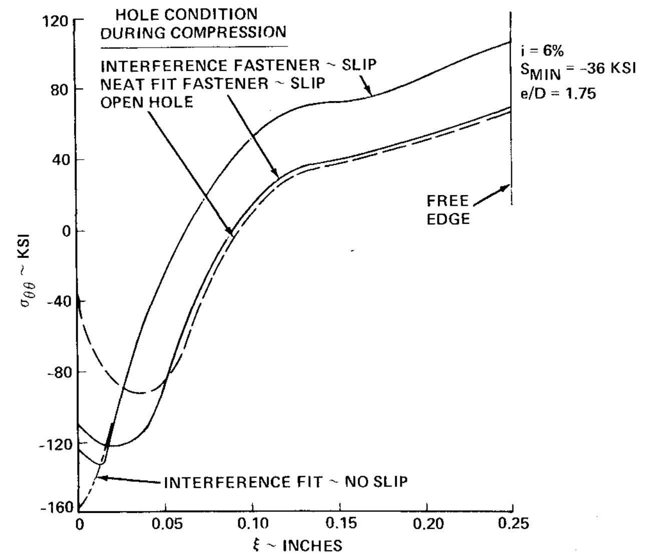


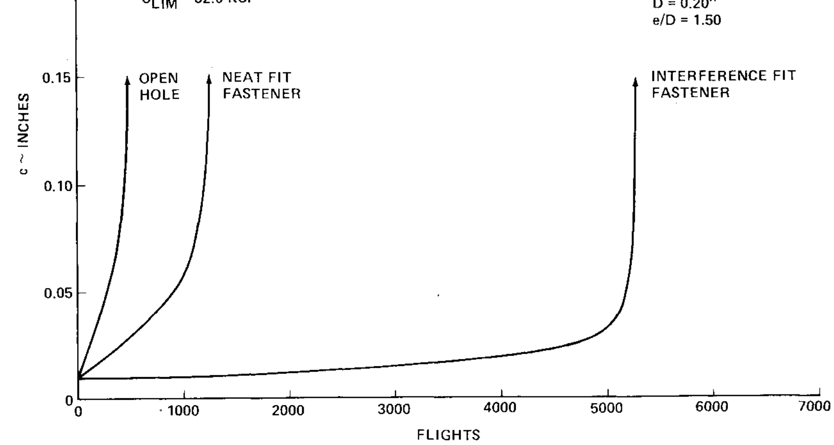
Fig. 11 Effect of fastener and compression load on residual stress due to coldworking.

One way to mitigate the effect of the remote compressive load on the residual stresses due to coldworking is to fill the hole with a fastener prior to the application of the remote load. Two possibilities were investigated, installing a neat-fit fastener and an interference-fit fastener. The FEA is used to simulate the response of the panel for each of these possibilities. For the case of the neat-fit fastener, the hole is constrained to remain circular during the application of the remote compressive load, i.e., no radial motion of the hole boundary is permitted relative to the center of the hole. Two variations of this analysis are carried out for the interference-fit fastener case. In the first case, slip (tangential motion) along the hole boundary is permitted. In the second case, no slip (tangential constraints) along the hole boundary is imposed. Results are presented in Fig. 11 where it is observed that the presence of the neat-fit fastener provides more residual compression stress at the hole edge. The fastener provides a load transfer mechanism across the fastener-sheet interface, reducing the stress concentration at the hole edge and hence rendering the coldworking more effective. The case of slip at the fastener-hole interface retains slightly less compressive residual stress than the no-slip case. Since the shear stresses along portions of the fastener-hole interface indicate evidence of slip according to the criterion of Eq. (6) (with $\mu = 0.4$), and since it represents a conservative situation, slip conditions are assumed to occur for subsequent analyses.

The installation of an interference-fit fastener prior to the application of remote compression was analyzed and its effect is also shown in Fig. 11. The interference level is 1%, and is simulated in the FEA by uniformly expanding the diameter of the hole subsequent to the coldworking process. The resulting residual hoop stress distribution provides higher compressive stress at the hole edge, but less compression over most of the ligament. The higher compressive stress at the hole edge will increase crack-initiation life and crack-growth life for very short cracks. However, once the cracks are far from the edge they will grow more rapidly than for the case of the neat-fit fastener or the open hole. This is demonstrated by the crack-growth curves shown in Fig. 12. Also, the higher tensile stresses exhibited by the interference-fit fastener case are due to the prying action of the fastener on the surrounding material. For the interference-fit fastener case the slip condition at the fastener-hole interface reduces the residual compressive stresses locally at the edge of the hole, and thus makes more conservative crack-growth life predictions, as shown in Fig. 11.

The effect of the various hole conditions during the application of the remote compressive load on the crack-growth life is shown in Fig. 12. It is observed that the installed

Fig. 12 Effect of hole condition on crack-growth life (remote compression load = S_{min} = 60 ksi).



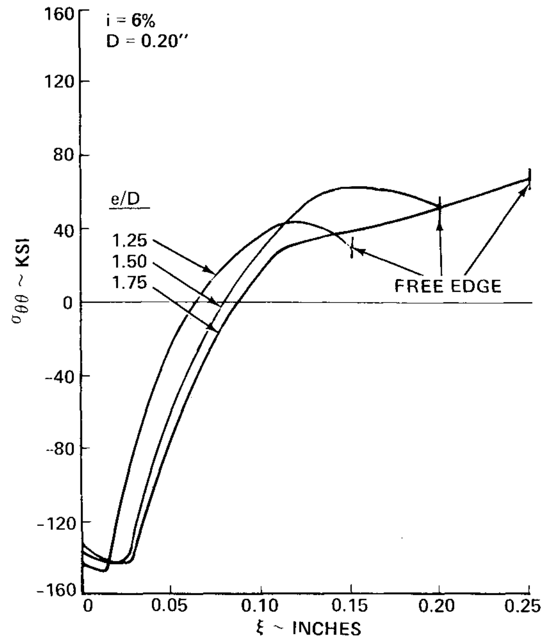


Fig. 13 Residual stresses due to coldworking (effect of varying edge distance open hole).

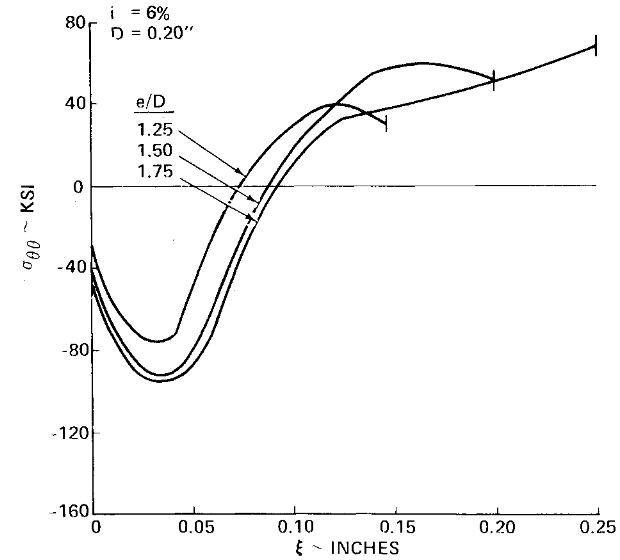


Fig. 14 Effect of edge distance stress (open hole and 36 ksi compression).

fasteners provide significant increase in crack-growth life, with the interference-fit fastener being more effective than the neat-fit fastener. This result is as expected. For the present case, the applied stress intensity factor (see Fig. 7) must also include the effects of the fastener. This was taken into account by an analysis of a hole with an interference-fit fastener in an infinite plate.[24] The same analysis was applied to the present case. The present analysis assumes that the residual stresses are those calculated for the uncracked structure and do not change with changing crack length. In the case of the interference pin, the wedging action of the pin will be reduced as the crack length increases, altering the residual stresses so that they approach the neat-fit fastener case for large crack length. From this point of view, the interference-fit fastener case is conservative.

Another practical variable that was investigated is the effect of varying the ratio of the edge distance to diameter (e/D) on the crack-growth life. Finite element models were made for configurations having e/D ratios of 1.25, 1.50, and 1.75. Residual hoop stresses in the ligament are presented in Fig. 13 for the cases cited. It is noted that the residual compression stresses as the edge of the hole vary only slightly with changes in e/D as they approach a limiting value set by the yield stress. However, for the two smaller e/D cases, the shape of the curves near the free edge is different than for $e/D = 1.75$. This change of shape is due to the entire ligament yielding during coldworking.

The effect of applied remote compression stress is treated next. Resulting residual hoop stresses in the ligament are shown in Fig. 14 for three variations of e/D. As already demonstrated in Fig. 10, the application of the remote compression reduces the levels of compressive residual stress near the edge of the hole, thus reducing the effectiveness of the coldwork.

The results of the coldworking parametric studies were applied to the prediction of fatigue crack-growth test data. The tested configuration has an e/D value $= 1.50$, a mandrel interference i of 6%, and was subjected to the randomized $F \times F$ fatigue load spectrum. In calculating K_R the 36 ksi remote compression load was taken into account. The coldworked specimens were not precracked so the cracks were initiated and propagated by fatigue. These cracks are part-through cracks, whereas the previous calculations were performed for through cracks. Predictions and test data are presented in Fig. 15. The coldworked hole analysis predicts a shorter crack-growth life as compared to the test data by a factor of two, and is therefore conservative.

Also shown in Fig. 15 are test data and analysis for non-coldworked holes subjected to the same geometry and loads. Here the analysis and test data correlate well. The test data indicates that for these conditions, coldworking increases the

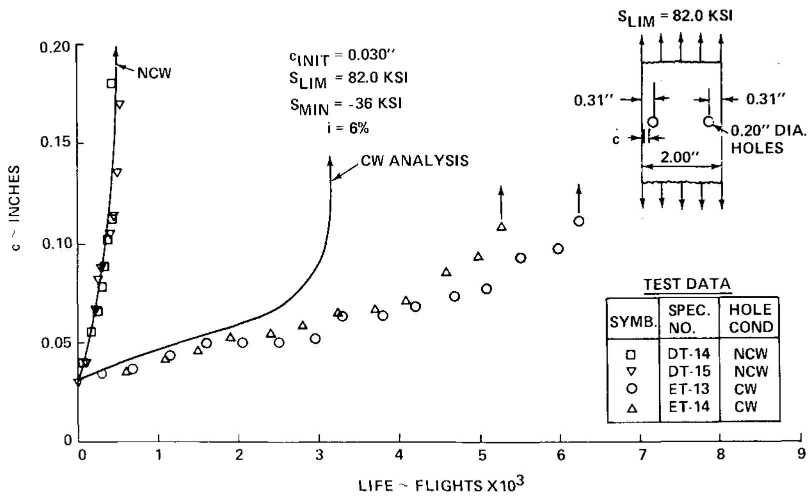


Fig. 15 Effect of coldworking on fatigue crack-growth life (open hole).

crack-growth life by a factor of ten. The analysis predicts an increase of about five times the life.

Conclusions

A detailed investigation of the effects of coldworking fastener holes located near the free edge of a structural component has been performed. The analytical techniques used include elastic-plastic finite element analysis to predict applied and residual stresses in the region of the hole, the weight function approach to calculate residual stress intensity factors from the predicted stress distributions, linear superposition of applied and residual stress intensity factors, and crack-growth life predictions using the multiparameter yield zone load-interaction model. From the results presented the following can be stated:

1) The multistep path-dependent process used to calculate residual streses provides reasonable results and predicts the effects of varying mandrel interference, edge distance, applied remote compression loads, fastener-hole slip vs no-slip conditions.

2) The presence of neat- and interference-fit fasteners are beneficial in mitigating the detrimental effects of applied remote compression loads on the beneficial residual stresses resulting from coldworking.

3) Permitting slip at the fastener-hole interface is conservative with respect to enforcing a no-slip condition.

4) Omitting the effects of remote compression loads on the residual stresses around coldworked holes will result in unconservative crack-growth life predictions.

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