Residual Strains Surrounding Split-Sleeve Cold Expanded Holes in 7075-T651 Aluminum

R. E. Link*
David Taylor Research Center, Annapolis, Maryland 21402
and
R. J. Sanford†
University of Maryland, College Park, Maryland 20742

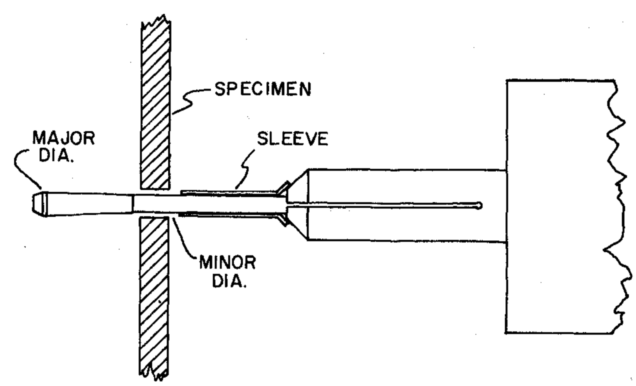
Measurements of the residual displacement fields surrounding cold expanded holes were made by using several optical techniques for experimental strain analysis. The residual strain fields were computed from the displacement field data for two levels of cold expansion. The experimentally determined results were compared with theoretical predictions of the displacement and strain fields. The results show that the presently available theories do not accurately predict the residual strains. This may be due, in part, to the three-dimensional nature of the split-sleeve cold expansion process. Finally, the results of this investigation are compared with the results of another investigator.

Introduction

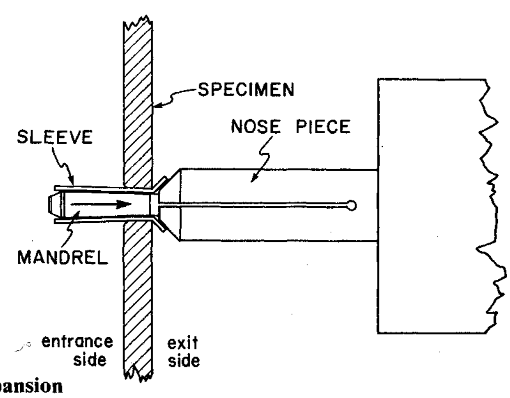
THE presence of fastener holes in a loaded structural element has a limiting effect on the fatigue life of the structure due to the stress concentration at the hole boundary. In order to minimize the detrimental effect of the stress concentration, it is common practice to prestress fastener holes by installing interference-fit fasteners or by cold working the holes prior to installation of the fastener, thereby introducing residual compressive stresses at the boundary of the hole. The residual stresses are a result of plastically deforming the material surrounding the hole.

The cold working process used in this investigation was a split-sleeve cold expansion process marketed by Fatigue Technology Inc. of Seattle, Washington. In this process, a hardened, stainless-steel split sleeve is placed over a tapered mandrel, and the mandrel/sleeve combination is inserted into a hole (see Fig. 1a). The mandrel is then drawn back through the hole while the sleeve is retained in the hole by the nosepiece of the mandrel puller as indicated in Fig. 1b. As the major diameter of the mandrel engages the sleeve and the hole, interference among the mandrel, the sleeve, and the hole causes plastic deformation of the material adjacent to the hole. The split sleeve serves two purposes. The sleeve is prelubricated and prevents galling of the hole wall since there is no movement of the sleeve relative to the hole wall during the expansion process. The mandrel slides along the inside of the sleeve, which has a molybdenum-disulfide lubricant on its inner diameter. The sleeve is discarded after it has been used. The presence of the split in the sleeve allows for the sleeve to be pushed past the major diameter of the mandrel before the mandrel is inserted into the hole, providing for a one-sided operation. This is important from a practical standpoint. Because of the split in the sleeve, there is a small discontinuity along the hole wall where the split in the sleeve is oriented. Fatigue tests of split-sleeve cold expanded holes indicate that there is no measurable effect of the discontinuity on the fatigue life.[1,2] The hole is post-reamed after cold expansion to ensure that the hole is circular before a fastener is installed.

There is no precise method for determining the optimum amount of cold expansion to apply to a hole for any given application. Current methods of optimizing the amount of expansion rely on conducting a series of fatigue tests for several levels of cold expansion and making a selection based on the improvement in fatigue life. Typical improvements in the fatigue life of fastener holes that have been cold expanded are 3:1 or greater.[1] While this approach may prove satisfactory for many applications, it does not provide much insight into the mechanics of the cold expansion process. An alternative approach is to quantify the residual stress and strain fields as a



a) One-sided insertion of tooling



b) Expansion

Fig. 1 A schematic representation of the split-sleeve cold-expansion process.

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*Mechanical Engineer, Fatigue and Fracture Branch. Associate Member AIAA.

†Professor, Department of Mechanical Engineering.

function of cold expansion and material properties. This type of approach would provide a better understanding of how the residual stress fields act to improve the fatigue life and also provide guidance on optimizing the process for different materials and hole sizes.

Since it is not possible to measure the residual stress field directly, one must measure the residual displacement or strain field and infer the residual stresses from the strains. The measured strain field can be compared with theoretical predictions of the residual strain fields. If any of the theories are to provide reasonable accounts of the residual stress fields, they must be able to accurately predict the strain field as well.

Many theories have been developed to predict the residual stress distribution due to the permanent enlargement of a hole in a sheet.[3-10] All of the theories assume that the deformation is radially symmetric and that the deformation is a result of a uniform pressure or displacement applied to the hole boundary large enough to cause yielding of the material adjacent to the hole wall. All of the theories consider small deformations only. Most of the theories assume the material to be in a state of plane stress,[3-8] while two of them assume a state of plane strain.[9,10] The theories also make assumptions about the material behavior. The Taylor theory[4] assumes that the material is perfectly plastic. The theories of Nadai,[3] Carter-Hanagud,[9] Hoffman-Sachs,[10] Alexander-Ford,[7] and Rich-Impellizzeri[8] assume that the material behaves in an elastic, perfectly plastic manner. Two of the theories, Hsu-Forman[6] and Mangasarian,[5] assume that the material can be represented by a Ramberg-Osgood uniaxial stress-strain relation. The possibility of secondary compressive yielding occurring during elastic unloading is addressed by the Rich-Impellizzeri[8] and Alexander-Ford[7] theories. A complete summary of these theories is presented in a dissertation by Poolsuk.[11]

It is questionable whether or not these theories can be used to accurately predict the residual stresses or strains surrounding cold expanded holes because the boundary conditions assumed by the theories do not match those of the split-sleeve cold expansion process. The split-sleeve cold expansion process does not provide for a uniform, through the thickness, expansion of the hole. The process is three dimensional in nature with the expansion occurring incrementally through the thickness. A considerable amount of compression in the thickness direction is also present as the mandrel is being pulled through the hole.

Numerous experimental investigations of the strain distribution surrounding cold worked holes have shown only marginal agreement between the predicted and the measured strains.[11-16] The experimental investigations have suffered from an inability to make precise measurements of the strain distribution very close to the hole boundary. The purpose of this investigation was to accurately measure the residual strain distribution surrounding split-sleeve cold expanded holes in 7075-T651 aluminum. These measurements could be used to evaluate the applicability of the available theories to the cold expansion process and to help develop guidelines for optimizing the cold expansion process for different materials and applications.

Experimental Investigations

Experimental measurements of the residual strain distribution surrounding split-sleeve cold expanded holes were accomplished by utilizing a variety of optical techniques of experimental strain analysis. These techniques included moiré interferometry,[17] speckle photography,[18] and micromoiré, a new technique developed in the course of this investigation.[19,20]

The material used in all tests was 1/4-in.-thick 7075-T651 aluminum plate. Typical tensile properties for this material are a yield strength of 80 ksi and an ultimate tensile strength of 85 ksi. All of the specimens were taken from the same sheet of material. The measurements were taken on isolated holes, remote from any boundaries. The ratio of the distance to the nearest free boundary b to the hole radius a was $b/a \geq 12$ for all cases as shown in Fig. 2. The holes were prepared by drilling to approximately 0.206 in. and then reaming to the desired initial hole diameter to produce a round hole with clean walls. The hole diameters were measured with a traveling microscope to the nearest 0.0001 in. The measurements were repeated for several different orientations of the hole, and measurements from the front and back of the specimen were averaged to determine the initial and final hole diameters. In all cases, the expanded holes had a larger diameter on the exit side where the nosepiece of the puller reacted against the specimen. Once a hole had been expanded, it was no longer perfectly circular. The presence of the split caused the deformation to be nonuniform around the circumference of the hole. The greatest amount of expansion occurred adjacent to either side of the discontinuity. Table 1 is a list of the initial and final hole diameters along with the amount of expansion for each of the tests reported.

Table 1 Summary of initial and final hole diameters and cold expansion levels

Test No.	Initial hole diameter, in.	Final hole diameter, in.	Cold expansion,%
CX-2	0.2260	0.2330	3.1
CX-6	0.2260	0.2332	3.2
CX-14	0.2308	0.2424	5.0
CX-18	0.2262	0.2319	3.0

Moiré interferometry was used to measure the residual displacement field remote from the hole boundary. This technique is a high-sensitivity method developed by Post[17] for measuring in-plane displacements. A typical fringe pattern from a 5% cold expanded hole is shown in Fig. 3. The grating frequency was approximately 5000 lines/in. A fringe multiplication factor of two was used. The loops of the fringes are symmetric with respect to the vertical centerline of the hole. The slight downward tilt of the fringes indicates that the expansion is not truly radial and that the displacements rotate symmetrically about a point just below the center of the hole.

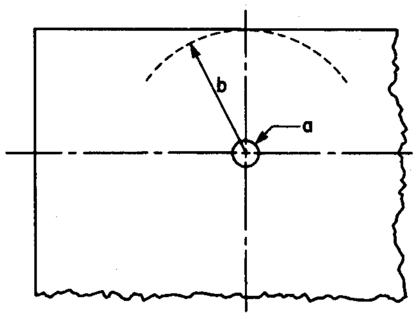

Fig. 2 Geometry of the specimens used in this investigation.

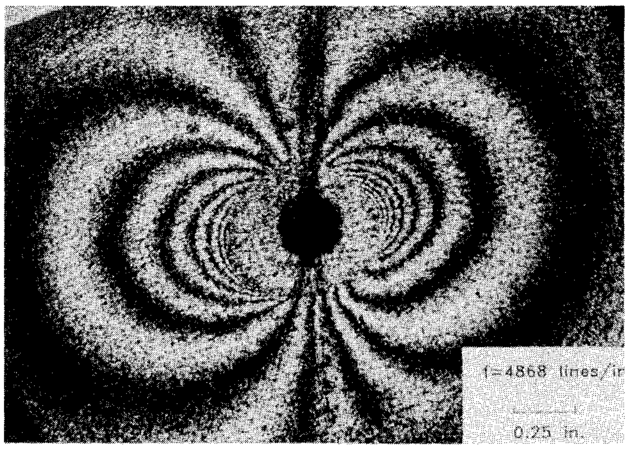

Fig. 3 Moiré fringe pattern from test CX-15, 5% expansion, entrance side.

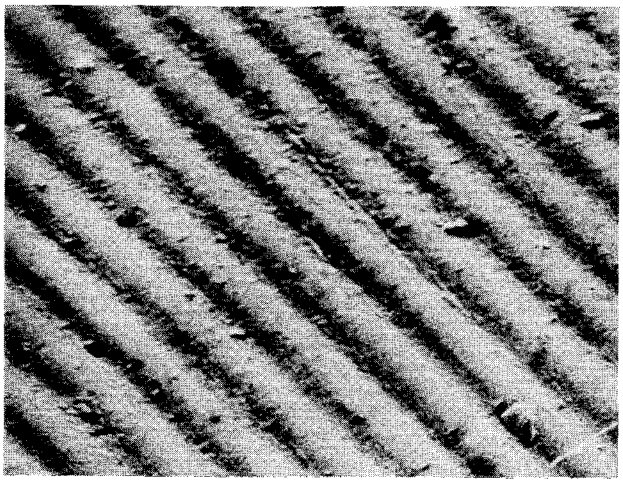

Fig. 4 Scanning electron micrograph of the undulating surface of the mirrored phase grating applied to the specimens for moiré interferometry and micromoiré.

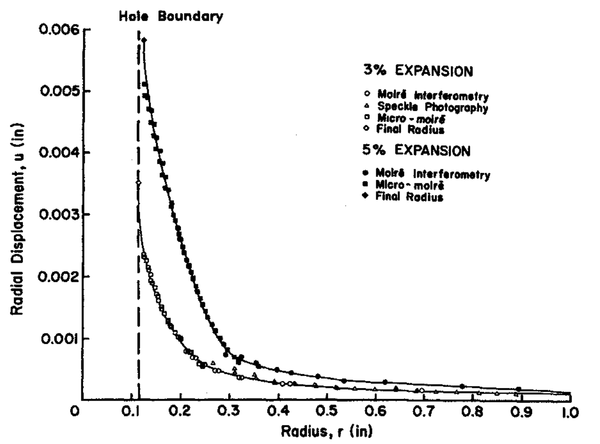

Fig. 5 Residual radial displacements from the entrance side of the hole for two levels of cold expansion.

The displacement of any point in the field is given by the relationship

$$u = N/f$$

where u is the displacement of the point in a direction normal to the grating lines, N the fringe order, and f the frequency of the reference grating. The displacements were determined along radial lines oriented at 90 deg to the discontinuity and plotted as a function of radius. The formation of a circular shadow around the hole due to excessive upsetting of the material immediately adjacent to the hole prevented any displacement field information from being obtained in the region of primary interest—very near the hole boundary.

In order to obtain precise measurements of the displacement field in the region near the hole boundary, two alternative optical techniques were investigated. Speckle photography was used with limited success. This method involves illuminating the specimen surface with a coherent light source (i.e., laser) and photographing the "speckles," which appear on the surface. The specimen is deformed, and a second exposure of the surface is made on the same sheet of film. The speckles move due to the deformation, and the displacement information may be recovered by optical processing of the doubly exposed film. The displacements measured using this technique agreed with those from moiré interferometry, but decorrelation of the speckles very near the hole boundary prevented this technique from being successful in this area.

A new technique, micromoiré, was developed and used to obtain the displacement information in this region. The micromoiré method made use of the same grating that was used to perform the moiré interferometry. The new method takes advantage of the fact that the mirrored phase grating, which is approximately sinusoidal (see Fig. 4), takes on the characteristics of an amplitude grating when viewed through the narrow light path in the optical microscope. In the application of this method to the cold expansion process, the undeformed grating at the periphery of the hole was photographed through the microscope at a magnification of 50×. After the hole was ex-

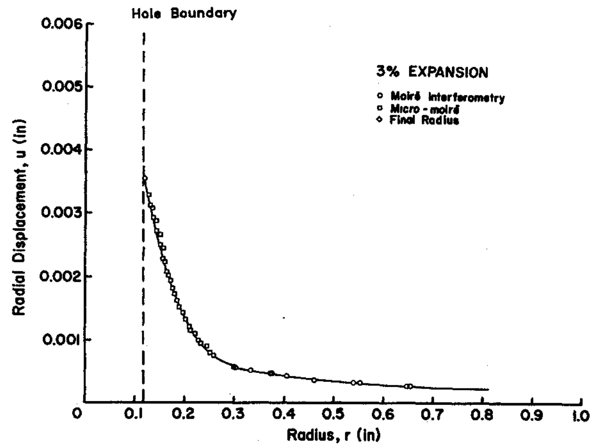

Fig. 6 Residual radial displacement from the exit side of the hole for a 3% expansion.

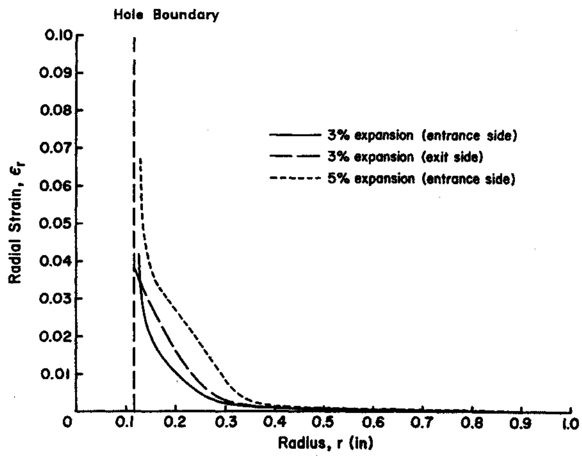

Fig. 7 Residual radial strains along a line oriented at 90 deg to the discontinuity.

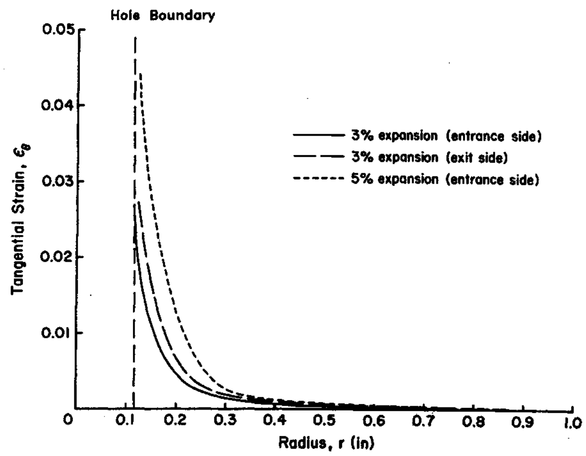

Fig. 8 Residual tangential strains along a line oriented at 90 deg to the discontinuity.

panded, the deformed grating was again photographed at the same magnification. Superposition of the negatives from the undeformed and deformed states produced classical moiré fringes, which were analyzed using standard moiré methods. Because of the very small field of view under the microscope (0.08×0.10 in.), it was necessary to take several overlapping exposures in a radial pattern in order to map the deformations out to the region where the moiré interferometry measurements began. Further details of the experimental techniques used in this investigation are contained in Refs. 19 and 20.

Results

The residual radial displacements from the entrance side of the specimen along a line oriented at 90 deg to the discontinuity are shown in Fig. 5 for two levels of cold expansion. Note the large number of data points all the way up to the hole boundary. Also notice the agreement between the measurements made using speckle photography and moiré interferometry on the entrance side of the hole. Results from the exit side of the specimen for a 3% expanded hole are shown in Fig. 6. In order to smooth the data before differentiating to determine the strains, a "best-fit" line was drawn through the data. The best-fit line was then digitized and stored for a later analysis.

For an axisymmetric problem, the strains at any point are given by the relations[21]

$$\epsilon_r = du/dr$$

$$\epsilon_t = u/r$$

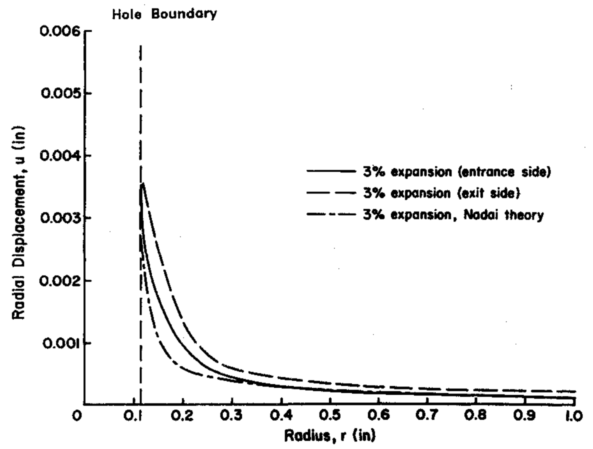

Fig. 9 Comparison of the residual radial displacements from experimental determination with the predictions of the Nadai theory for a 3% expansion.

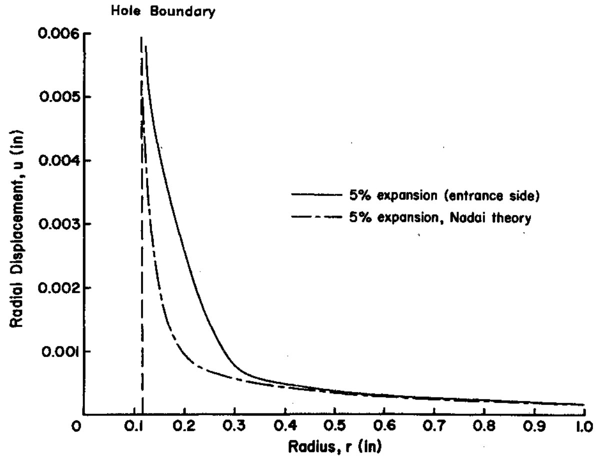

Fig. 10 Comparison of the residual radial displacements from experimental determination with the predictions of the Nadai theory for a 5% expansion.

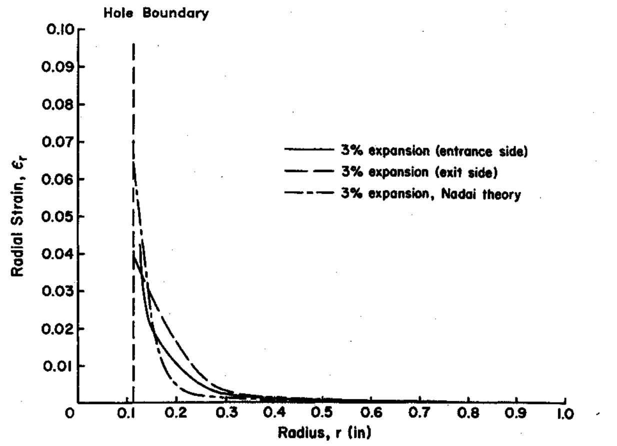

Fig. 11 Comparison of the residual radial strains from experimental determination with the predictions of the Nadai theory for a 3% expansion.

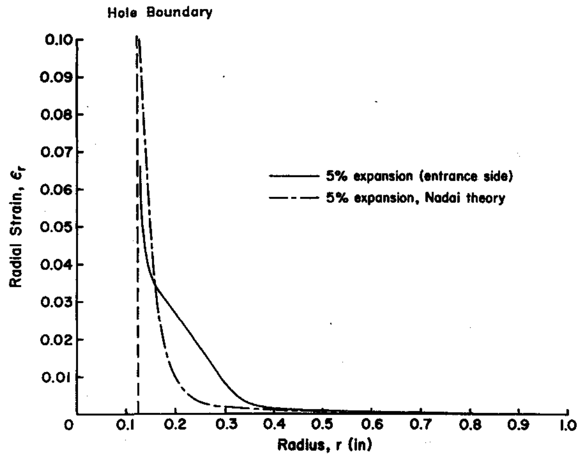

Fig. 12 Comparison of the residual radial strains from experimental determination with the predictions of the Nadai theory for a 5% expansion.

where u is the radial displacement and r the radial position of the point. The radial strains were calculated by fitting the digitized displacement data to a floating, seven point, least-squares quadratic function and then taking the derivative of the function at the midpoint of each data subset. The tangential strain was calculated by taking the ratio of u/r at each data point.

The residual strains calculated along a line oriented at 90 deg to the discontinuity for the two levels of cold expansion are shown in Figs. 7 and 8.

Discussion

There is a significant difference in the shape of the residual displacement curves from the entrance and exit sides for the 3% expanded hole. This difference suggests that the cold expansion process is three dimensional with the exit side of the specimen experiencing a larger degree of expansion. As the level of cold expansion is increased, the nature of the residual displacements changes systematically. At higher levels of cold expansion, the displacement curves begin to straighten out in the range of $r = 0.15$ in. to $r = 0.3$ in. (this corresponds to the range $1.5 \geq r/a \geq 3$). The straightening of the displacement curve could be indicative of reversed yielding in the plastic zone when the mandrel is removed and the material surrounding the hole unloads elastically. (The amount of unloading could be great enough so that the material immediately surrounding the hole is forced to yield in compression.) Another possibility is that the material has strain hardened sufficiently to cause a spreading of the strain field.

The results of the experimentally measured residual displacements and strains are compared with predictions made using the widely accepted Nadai theory[3,11,13,15] in Figs. 9–14. The residual displacements are shown in Figs. 9 and 10. The Nadai theory underestimates the total residual displacement by 23% for the case of 3% expansion and by 14% for the case of 5% expansion. The gradients near the hole boundary are very different also. This leads to differences between the predicted and measured residual strains, which are plotted in Figs. 11 through 14. In general, the agreement is poor. The experiments demonstrate that the influence of the cold expansion process extends further into the material than predicted by the theory. It is clear from the residual displacement and strain plots in Figs. 9–14 that for the large degrees of cold expansion used in this investigation (3% or more), the Nadai theory does not provide an accurate representation of the residual displacements and strains. The influence of the residual strain fields persists further into the material than the theory predicts. These differences may be due to the fact that the assumptions and boundary conditions of the theory do not properly model the split-sleeve cold expansion process.

Cloud[15,16] made measurements of the residual strain fields surrounding cold-expanded holes using a classical moiré technique. His technique did not provide for a great number of data points in the region very near the hole boundary. The cold expansion process, which he investigated, was slightly different from the split-sleeve process. The process investigated by Cloud uses a solid sleeve, which remains in place after expanding the hole rather than the split-sleeve, which is removed after the hole has been cold expanded. The size of the

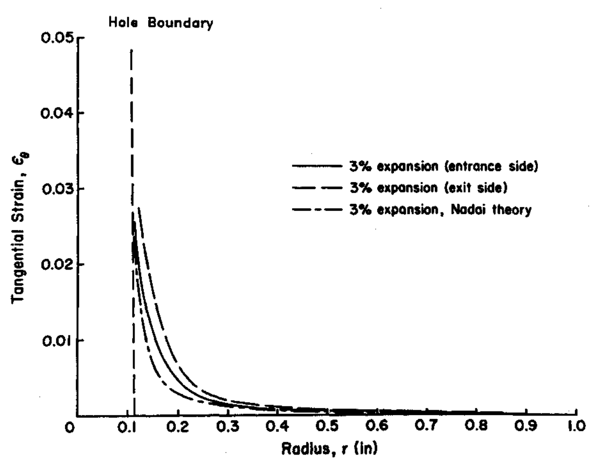

Fig. 13 Comparison of the residual tangential strains from experimental determination with the predictions of the Nadai theory for a 3% expansion.

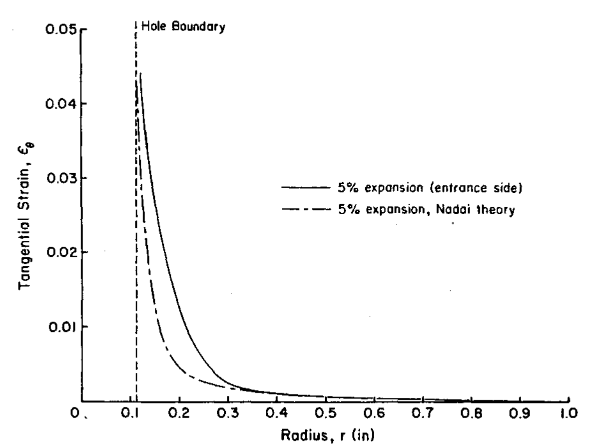

Fig. 14 Comparison of the residual tangential strains from experimental determination with the predictions of the Nadai theory for a 5% expansion.

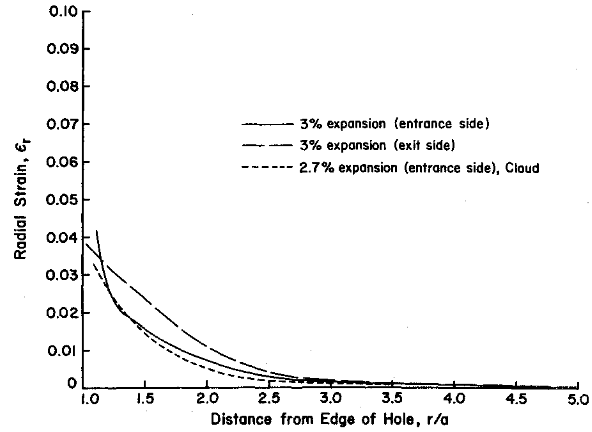

Fig. 15 Comparison of the residual radial strains for a 2.7% expansion measured by Cloud with the results for a 3% expansion.

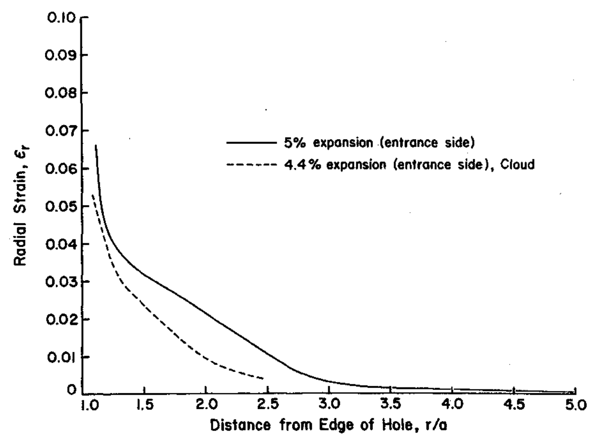

Fig. 16 Comparison of the residual radial strains for a 4.4% expansion measured by Cloud with the results for a 5% expansion.

holes that he investigated was slightly larger than those in this investigation (nominal diam = 0.26 in.). Cloud does not present results for the residual displacements but only for the residual radial strains. In addition, the technique utilized by Cloud did not provide displacemet data as close to the hole boundary as this investigation. Nonetheless, it is possible to make some comparison between Cloud's results and the present investigation. All of Cloud's data for aluminum specimens were taken on the entrance side of the hole. In order to compare the results of Cloud with those of the present investigation, the results of both investigations were normalized with respect to the initial hole diameter. Figures 15 and 16 compare the residual radial strains measured by Cloud with the results from this investigation. The results of Cloud are for slightly lower levels of expansion than were used in this investigation (2.7 vs 3% and 4.4 vs 5%) The agreement between the two sets of data is reasonably good. Close to the hole boundary, the strains for the 3% expanded hole are larger than those for the 2.7% expanded hole as expected. Qualitatively, the residual strains for the two levels of cold expansion are similar. Both strain plots show a straightening of the curves in the region from $r/a = 0.5$ to $r/a = 2$. The strains for the 5% expansion remain relatively straight to an $r/a = 2.75$. This is not surprising since the expansion is larger in this case.

Conclusions

Experimental measurements of the residual strain distribution surrounding split-sleeve cold expanded holes were accomplished by using a variety of optical techniques of experimental strain analysis. These techniques included moiré interferometry, speckle photography, and micromoiré. The combination of experimental methods made it possible for the first time to precisely determine the displacement field all the way to the hole boundary.

The experimentally determined residual strains were presented and compared with theoretical predictions and with the experimental results of another investigation. The experimental results indicate that the residual strain fields extend further into the surrounding material than predicted by theory. A possible explanation for the differences between the theoretical predictions and the experimental measurements is the fact that the boundary conditions assumed by the theories do not model the cold expansion process accurately enough.

Acknowledgments

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