Measurement of Strain Fields near Coldworked Holes

High-resolution grating photography, optical data processing, and digital data reduction extend power and simplicity of moiré study of elastic-plastic problem

by Gary L. Cloud

ABSTRACT—Residual strains near coldworked holes were measured for several degrees of radial expansion. Moiré-grating photography created magnified replicas of deformed gratings. Fringe patterns with sensitivity multiplication and S/N improvement were obtained by optical data processing and by using slotted apertures for photography. Computer data reduction and plotting provided the required strain maps.

Purpose and Scope of Investigation

The goal of this investigation was to measure residual-surface-strain fields created by coldworking holes to various degrees as a means of improving the fatigue performance of structural components. An important auxiliary objective was to choose and develop measurement techniques which were appropriate to this complex problem and which could be reduced to a procedure simple enough to be performed routinely by technical assistants using unsophisticated equipment.

The coldworking process marketed by J.O. King Incorporated of Atlanta, Georgia was the only one considered in this study, although the results should hold for certain other processes. Attention was directed mainly upon radial-strain components, but tangential strains were required for some levels of radial interference. The effects of remote loads, near plate edges and nearby holes were to be established as a part of the continuing study, and the methods chosen had to accommodate that requirement.

This report concentrates on the following aspects of the investigation:

(1) Technical considerations leading to choice of measurement technique.

(2) Description of apparatus and procedures developed to satisfy the technical requirements as well as those imposed by economic, time, available equipment, and technical-manpower considerations.

(3) Typical results.

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Paper was presented at 1979 SESA Spring Meeting held in San Francisco, CA on May 20-25.

Original manuscript submitted: November 3, 1978. Final version received: September 19, 1979.

Space limitations prohibit presentation of technical detail, and the discussion herein is of quite general nature. Discussions of apparatus, theory and procedure, as well as complete results, are contained in a related technical report.[1]

Background

Because they create areas of high stress and increase the number of potential crack-initiation sites, holes often shorten the fatigue life of structural components and are, therefore, a source of concern to the designer. For example, a review of aircraft structural failures has shown that cracks which began at fastener holes were the main cause of ⅓ of early failures.[2] it is important to develop better understanding of crack initiation and growth from holes and also to devise techniques for decreasing the tendency for failure to begin at holes.

One approach to improving the fatigue performance of a component containing a hole is to plastically expand the hole. Several proprietary schemes have been invented for accomplishing this coldworking in an efficient way.[3] While evidence supports the assertion that coldworking improves fatigue life,[4,5] the degree of improvement for a given amount or mode of coldworking is not settled.

Design procedures for coldworked holes are still in the early stages of development. It is not within the scope of this paper to discuss existing theoretical models in any detail, but mention of certain aspects of these models helps to justify and guide efforts to measure strain fields near holes. Grandt[6] and Grandt and Gallagher,[7] for example, have adapted the methods of fracture mechanics to develop procedures which account for the effects of coldworking at fastener holes. Their approach has been tested to a degree by Cathey[8] and by Grandt and Hinnerichs.[9] These fracture mechanics calculations, and probably any other analysis scheme which could be devised, require knowledge of the stress field around the nonflawed hole after coldworking.

Little information exists about the stress fields induced by inelastic radial expansion of holes. Noteworthy is the work of Sharpe,[10] Chandawanich and Sharpe,[11] and Poolsuk and Sharpe[12] who have drawn together theoretical models and performed experiments to test them as well as to investigate the initiation and propagation of fatigue cracks from coldworked fastener holes. Among other theoretical approaches, these investigators checked the simple analytical solution developed by Potter and Grandt,[13] as well as the measurements and finite-difference analysis of Adler and Dupree,[14] the closed form solution of Hsu and Foreman,[15] and the early theoretical solution of Nadai.[16] A simple experimental and analytical study of interference-fit fatigue-rated fasteners has been reported by Ford and his group.[17]

The studies mentioned above are deficient in one important aspect, they cover only few levels of coldworking. Chandawanich and Sharpe used two coldworking levels, one of which was thought to be close to the optimum value. Minimal evidence exists to show that this value does give the best fatigue performance.[4,5] Existing information about the stress-strain field near coldworked holes is not sufficient, then, to adequately test relevant theories or to serve as a data base for designers in doing fracture-mechanics calculations. Neither can one assess the effects of normal industrial tolerances upon the fatigue performance or the design procedures. The experimental investigation described herein was undertaken to narrow this gap in our knowledge.

Choice of Experimental Method

The problem of measuring strains in the vicinity of a coldworked hole is one which taxes the common techniques of experimental strain analysis. Characteristics of the technical problem which had to be considered when planning an approach included:

(1) The strain magnitudes were expected to range from about 10 percent compression to about 3-percent tension.

(2) There is considerable out-of-plane displacement near the hole.

(3) Extensive rumpling of the surface occurs in the zone of nonlinear deformation.

(4) The strain gradient is large in the region near the hole.

(5) The area of prime interest is close to a boundary.

(6) The sleeve which is used in the process protrudes slightly from the surface.

(7) Experiments were to take place in several nonreversible, nonrepeatable stages.

(8) A whole-field map of two principal-strain components for each stage was needed (principal directions established by symmetry).

One of several variations of modern moiré techniques appeared to satisfy best these conditions. The method is whole field and noncontacting; it offers the possibility of choosing sensitivity *after* the raw data have been permanently recorded; and it can yield correct results in regions of high strain gradient and near boundaries.

The decision was to utilize the moiré technique with gratings of 39.4 lines per millimeter (lpmm) or 1000 lines per in. (lpi) applied to the specimen. Because the specimen surface does not remain flat, a noncontacting procedure was developed which calls for photographing the specimen grating before and after coldworking the specimen. The photographic replicas were superimposed with one or more submaster gratings in an optical Fourier processor in order to form separate baseline and data moiré-fringe patterns. Fringe multiplication and pitch mismatch were introduced during this stage in order to obtain increased sensitivity and to improve interpolation. The moiré-fringe orders and their positions were obtained from the photographs in digital form. Displacement and strain distributions were generated and plotted using a digital computer. Summary descriptions of the steps involved in each stage of the investigation are given below.

Creation of Grating Photographs

For maximum flexibility in the moiré study, it was necessary to obtain good quality photographic replicas of the specimen grating in its deformed and original states. These photos were to be superimposed with submaster photoplates of various pitches which also had to be produced as part of the technique development. It was necessary, then, to create sharp specimen gratings, to perform high-resolution photography in order to record the specimen grating, and to create submaster grating replicas for use in optical processing.

Procedure Summary

(1) Master gratings of 39.4 lpmm were obtained and reduced photographically to create a set of working submasters of various grating spatial frequencies ranging from 39.4 to about 120 lpmm.

(2) After cleaning the polished specimen thoroughly, a thin coating of photoresist lacquer was sprayed onto its surface with an airbrush and the coating dried in low heat.

(3) A submaster grating was clamped to the coated specimen and the assembly exposed to unfiltered radiation from a mercury lamp in order to produce a contact image of the grating in the resist.

(4) Fiducial marks previously scribed were touched up, highlighted and identified.

(5) The specimen was placed in a special holder and the grating photographed on glass photoplates at low magnification (1.3 ×) with high-resolution technique.

(6) The hole in the specimen was coldworked.

(7) The specimen was returned to the holder; and the grating, now deformed by the coldwork treatment, was photographed again.

Master and Submaster Gratings

A grating having a spatial frequency of 39.4 lpmm on a 100 mm by 100 mm glass substrate was obtained from Photolastic Inc. of Raleigh, NC, USA, for use as a master grating. Submasters made from a deposited metal film grating obtained from Graticules Limited of England were used in the last stages of the experiment, and they gave better results. The making of full-size copies of moiré gratings has been thoroughly explored and explained by Luxmoore, Hollister and Hermann[18-20] and others. Their techniques have been used in this study with certain simplifications. Contact copies were made by a method similar to that employed by Chiang[21] on Kodak High-resolution plate (HRP), using for the light source a Durst enlarger head with a 150 mm Schneider lens at f5.6. The emulsion of the HRP was simply placed in contact with the emulsion side of the master and held in place by small weights. Only a thin film of Xylene was placed between the two to reduce the effects of possible lenticulation in the master grating.

Direct photographic reproduction was employed for manufacture of the several submaster gratings having various spatial frequencies. Several of each grating having spatial frequencies clustered near 30, 60 and 90 lpmm

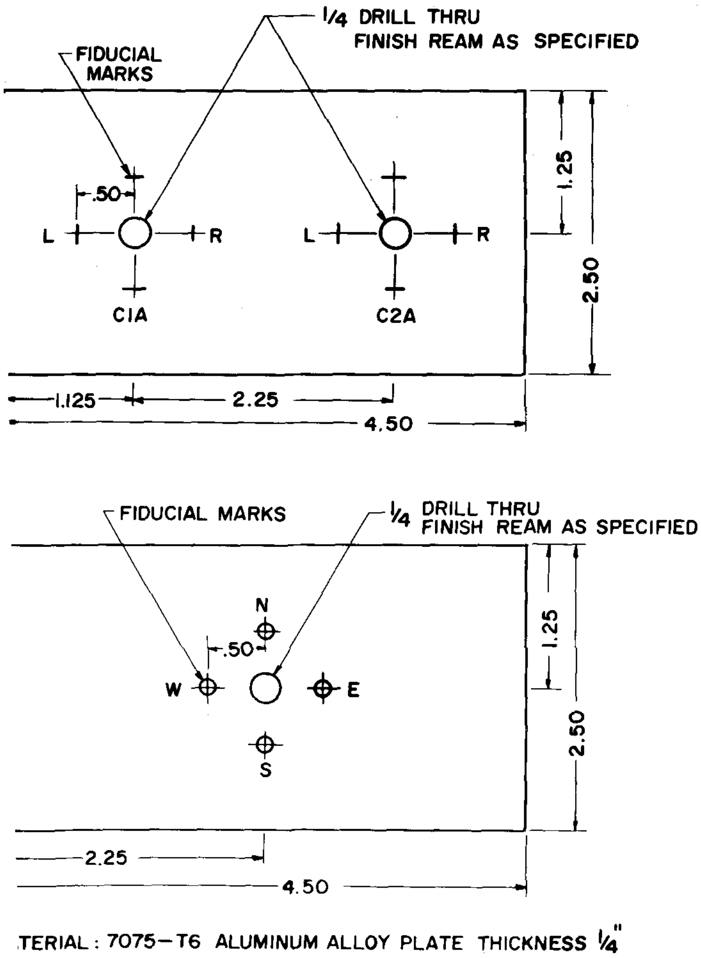

Fig. 1—Specimens used for measurement of strain near coldworked holes; typical fiducial markings shown

were produced. These values are 1, 2 and 3 times the fundamental spatial frequency of the specimen grating photographs plus various frequency mismatches. To produce these submasters, the master grating was held in a laboratory clamp base and backlit with light from a Kodak slide projector. A ground-glass plate was placed about 3 in. behind the grating to scatter the incident light. The other apparatus was the same as was used in photographing the specimen grating and is described below.

Both Kodak HRP and spectroscopic plate 649-F were used for the photo-reduced submaster. Grain was noticeable with the 649-F emulsion, but the gratings were sharp and of good contrast. The submaster gratings were checked by observing their diffraction efficiency by eye as they developed. It is important to realize that both the gross transmittance and the diffraction performance of the submaster must be complementary to the characteristics of the specimen photograph in the optical data-processing stage. For this reason, several different photoplates at each spatial frequency were produced. To some extent, the variation of density over the extent of each submaster plate which resulted from cosine^4 light fall-off proved useful in optical data processing. It tends to counteract the normal Gaussian distribution of light in the expanded laser beam to give a near-uniform field in the fringe photographs.

Specimens and Coldworking

Two types of specimens were used. Both are pictured in Fig. 1. The design with two holes was adopted as a means of saving material. Previous studies suggested that the two strain fields would not interact significantly given hole separations on the order of those used. In moiré work, where several stages of photographic processing are used, it is important to have adequate fiducial marks and identifying labels on the specimen surface. Scribed lines and self-stick lettering were utilized.

The specimens were sawn from a single plate of 7075-T6 aluminum alloy having 6.4-mm thickness. The sheet was the same stock as that used by Adler and Dupree[14] and by Sharpe and his co-workers;[10-12] so, direct comparisons are valid.

In the King process, a stainless-steel sleeve which carries an anvil on one end is inserted into the hole. A tapered mandrel is pulled through while the sleeve is supported on the anvil. The mandrel enlarges the sleeve and expands the hole enough to cause plastic deformation of the adjacent material. The sleeve remains in the hole but the anvil drops off.

The restriction to standard sizes of reamers, fastener sleeves, and mandrels limited the spectrum of coldworking levels to the following degrees of radial interference (mandrel radius plus sleeve thickness minus hole radius): 0.97 mm, .10 mm, .14 mm, .15 mm, .17 mm (2 specimens), .18 mm and .20 mm.

Specimen Grating

The photoresist approach to creating gratings on the specimen was chosen because it is fairly simple, requires minimal special equipment, and offers a possibility of baking and etching the grating to make it resistant to damage. Given the severity of the plastic deformation and the rumpling of the specimen surface near the hole along with the potential for mechanical damage to the specimen during various stages of the experiment, the etching capabilities seemed important. A further potential is that etched gratings could be used for studies at temperatures above which the photoresist vaporizes or burns. This capability has proved important in subsequent experiments, as have vacuum-deposited metal gratings.

The techniques described by Luxmoore, Hollister and Hermann[18-20] were adopted and adapted. These and additional techniques are described in the useful book by Vocke and Ullmann[22] and in the work of Naumann[23] and his colleagues. The photoresist chosen was Shipley AZ1350J provided by Shipley Co., Newton, Mass. 02162, USA. This particular resist is formulated for acid-resist coating on aluminum and its solids content is 30 percent. In order to produce coatings as thin as at first seemed necessary, the photoresist required thinning considerably in excess of the degree suggested by the manufacturer.

Conventional methods of applying the resist coating in the thickness and uniformity required tended to leave some buildup and sagging near the hole, which is the region of greatest interest. Attention settled on spraying with an airbrush.

The moiré grating was printed in the photoresist coating by a simple contact procedure in which the grating submaster was clamped to the specimen and the assembly exposed to light from a mercury lamp. The lamp was the light source in a Visicorder optical-chart recorder. This lamp has the power of only 100 watts, but its arc is so small that it was possible to bring the specimen to within 120 mm of the lamp without losing acuity or changing the grating pitch. Lenticular effects in the submaster were usually reduced by using a 50-percent aqueous glycerin solution between the emulsion and photoresist.

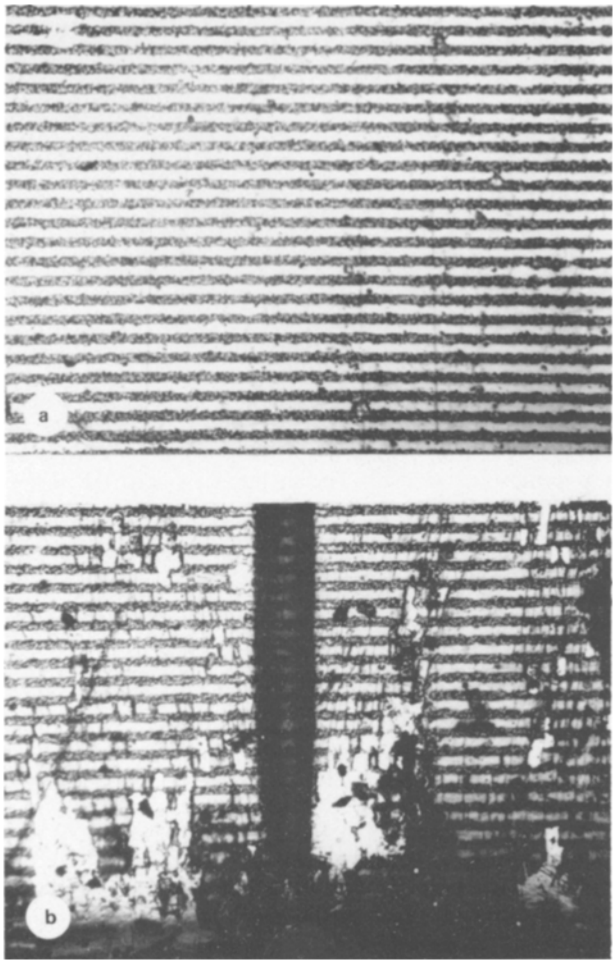

Fig. 2—Photomicrographs of 39-lpmm (1000-lpi) specimen grating in photoresist: (a) in small-strain region; (b) adjacent to hole in large-strain region

Figure 2 reproduces photomicrographs of typical specimen gratings in an unstrained state and after coldwork of the aluminum substrate. The damage to the specimen grating which is caused by the coldworking is readily apparent.

Photography of Specimen Grating

The system devised for photographing the specimen grating is shown schematically in Fig. 3. As noted earlier, this setup was similar to the one used for producing the submaster gratings. It was simple and gave good results with available equipment.

The camera used was a 10×12.5-cm Burke and James "Orbit" monorail which was stiffened with angle iron and weighted with lead blocks and steel plate. The lens was a Goertz red-dot Artar apochromat with focal length 24 cm and maximum aperture f9. The camera was set at full extension to give an image of the specimen which was magnified by a factor of about 1.3. The specimen in its specially designed holder, the illuminating source, and the camera rested upon a Gaertner optical table.

Focus of the specimen image is very critical in such a situation requiring high resolution. The ground glass of the camera was not satisfactory because it was too coarse and because such focus plates are often not exactly in the photoemulsion plane. For focusing, a blank plate of the same thickness and type used in the photography was developed, fixed and mounted in a plate holder. The image of the specimen in the emulsion was examined with an Edmund 50× magnifier which had been adjusted to focus in the emulsion plane while the magnifier base rested on the opposite side of the film plate. The image of the specimen grating could be checked over the whole area of interest for maximum sharpness and contrast. As a check on focus, parallax between the grating image and scratches in the emulsion were studied.

Although a monochromatic filter is usually specified with this type of high-resolution photography, it did not prove practical here because available light was so low that contrast and definition were lost with filtered light

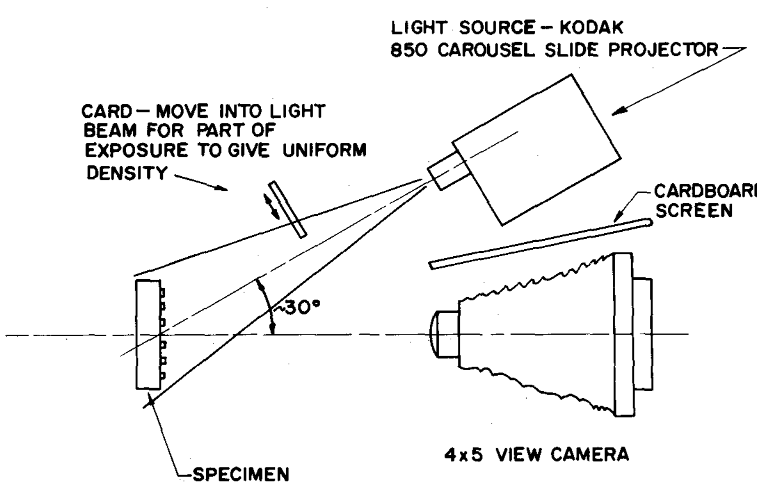

Fig. 3—Schematic of apparatus for photographing specimen grating

and the film used. This problem was believed to be caused by reciprocity failure as well as convection currents during the required long exposures. White light gave better results. The Goerz lens, which is a four-element symmetrical design, is well corrected for transverse and longitudinal chromatic aberrations. A small amount of lateral color was noticed at the extreme edge of the focus plate when examined with the magnifier, but the aberration was far from large enough to affect definition in the grating image.

Figure 4 is a medium-contrast magnified copy of a grating photograph as obtained by this procedure from a severely coldworked area of the specimen. While lacking something in quality, such photographs proved good enough to produce sharp fringes when optical processing was employed.

Slotted Apertures in Grating Photography

Forno[24] and Burch and Forno[25] have demonstrated that slotted apertures can be used to tune a camera lens to give sharpened photographs of grating structures, to improve depth of field, and to enhance the response of a photographic system to certain spatial frequencies which might be contained in a random pattern. The work of Burch and Forno seems directed mainly towards measurement of deformation and strain through elegant but simple improvements of the moiré and speckle techniques.

Cloud[26] described an extension of the concepts which are developed and utilized in the references mentioned above. Slotted camera apertures can be used for multiplication of grating spatial frequency in moiré photography. Sensitivity of the measurement, which is often a serious problem when measuring strains with the moiré method, can be increased several fold. Depth of field is increased, and a camera lens of 'ordinary' quality can be used to photograph the high-frequency gratings. The method gives improved rendering of grating lines when sensitivity multiplication is not needed. The photography of two-dimensional arrays (grid and dot patterns) is simplified. These improvements multiply any gains which are derived from coherent optical processing of the moiré photographs.

Slotted apertures were designed to fit behind the iris diaphragm inside the Goerz lens. Slot sizes and locations were calculated to tune the lens to spatial frequencies of 30 and 60 lpmm in the image plane for green light (corresponding to 39.4 and 78.8 lpmm in the specimen plane). Since the masks were to be placed near the iris, it was necessary to account for magnification of the mask by the rear-lens element. This magnification was found to be 1.09.

In establishing a slot width, which governs the bandpass of the tuned lens, it is necessary to account for the maximum and minimum grating frequencies which will be encountered in the strained grating. The masks used were designed for a fairly broad bandpass, giving a strain response of more than ± 10 percent.

Figure 5 shows micrographs of typical photoplates of the same specimen used for Fig. 4 taken with the apertures installed in the camera lens. Comparison of Figs. 5(a) and 5(b), which were recorded with the 30-lpmm mask (referred to image plane) with Fig. 4 suggests the degree of improvement which can be expected from using filter masks in photographing moiré specimen and master gratings. Especially important is the delineation of the grating in the areas where it cracked and flaked because of the plastic deformation of the specimen.

Figure 5(c) illustrates the grating frequency multiplication which can be obtained with slotted apertures inside a lens having a rather low upper-frequency limit. The grating in Fig. 5(c) is 60 lpmm on the film, which is equivalent to 78 lpmm (2000 lpi) on the specimen. Although this grating shows local nonuniformities, it produces very good moiré fringes when superimposed with an appropriate submaster.

Formation of Moiré-fringe Patterns

Although useful moiré-fringe patterns can be obtained by direct superposition of the grating photoplates with one another or with a grating submaster, such a simple procedure does not yield the best results, nor does it exploit the full potential of the information which is stored in the grating record. Increased flexibility and control of the measurement process can be had by utilizing

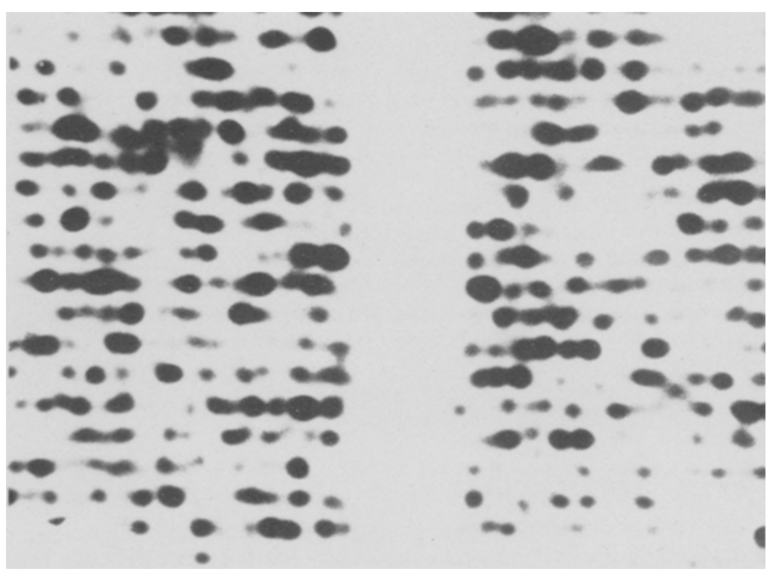

Fig. 4—Photograph of negative photoplate of specimen grating obtained on 649-F plate at f 11 with white light and no filter mask

some of the basic procedures of optical data processing.

Exploration or discussion of the relevant Fourier optics and diffraction theory are outside the scope of this paper. Of the many fine treatments in the literature, the papers of Van der Lugt[27] and Post[28-30] are especially useful, as is the landmark book by Guild.[31] The recent book by Vocke and Ullmann[22] contains valuable summaries of these ideas.

The advantages of optical-data-processing procedures quickly become apparent at this point. The baseline and deformed-grating data are permanently stored on glass photographic plates. It is possible to superimpose these plates with different submaster gratings or with one another in order to gain maximum useful sensitivity multiplication and to improve subsequent fringe reading and data analysis by optimizing the spatial-frequency mismatch of the superimposed gratings.

In practice, the specimen-grating photographs had a spatial frequency of 31 lpmm. These plates could be superimposed with submasters of around 90 lpmm to get a sensitivity multiplication of 3, or of 60 lpmm for a multiplication of 2. The various mismatches were chosen to yield the closest fringe spacing obtainable with good fringe visibility. Most grating photographs were processed with at least three mismatch levels and, sometimes, with more than one sensitivity multiplication factor for checking purposes and because it was not possible to always assess the quality of a dense fringe pattern through the camera viewfinder. It was possible, at this stage, to select submasters which had density and diffraction characteristics which balance the properties of the specimen grating to produce the best fringe pattern. Also, the diffracted ray group which gave best fringe visibility could be selected.

The optical data-processing system which was developed is pictured schematically in Fig. 6. This apparatus has been subject to a continuing process of modification and upgrading.

Samples of typical moiré-fringe patterns obtained by optical data processing are reproduced in Fig. 7.

Summary of Optical Processing

(1) A photoplate of the undeformed grid was superimposed with a submaster grating having a spatial frequency of 3 (sometimes 2) times the frequency of the magnified specimen grating plus or minus a small frequency mismatch.

(2) The superimposed gratings were clamped together and placed in a coherent optical processor and adjusted to produce a correct baseline (zero strain) fringe pattern at the processor output, where it was photographed.

(3) Steps 1 and 2 were repeated with the photograph of the deformed grating in order to create the 'data' or 'at strain' fringe pattern.

(4) Steps 1-3 were repeated with other submaster gratings to produce fringe patterns having different pitch mismatch and, in some cases, different sensitivity multiplication.

(5) The fringe patterns were enlarged and printed in a size equivalent to about 7 times actual specimen dimensions with medium contrast.

(6) The prints were sorted and coded for identification during the digitizing and data-reduction steps.

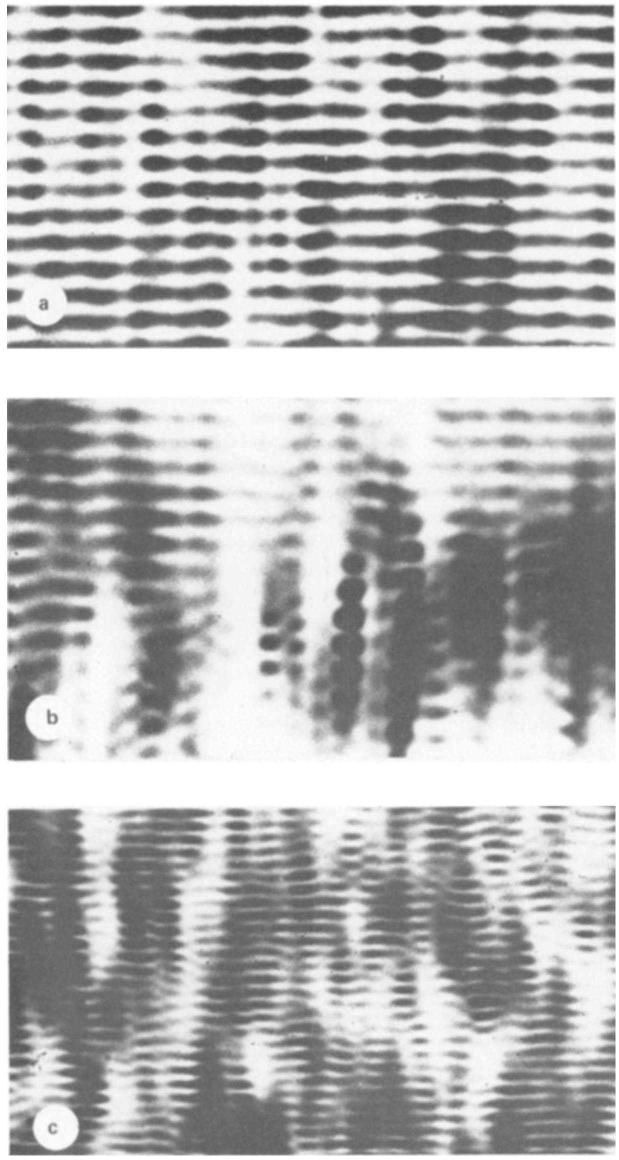

Fig. 5—Photomicrographs of negative photographs of specimen grating obtained on 649-F plates with slotted aperture masks and white light: (a) in small-strain region with aperture having 39-lpmm (1000-lpi) center frequency at specimen; (b) same as (a) but in large-strain region near hole; (c) in small-strain region with aperture having 79-lpmm (2000-lpi) center frequency at specimen

Reduction of Moiré Data

The volume of moiré data accumulated made numerical processing attractive. A data-reduction scheme was developed which incorporated most of the advantages of high-speed computing while retaining some desirable features of cruder techniques, such as allowing examination of intermediate results and the introduction of a controlled small degree of data smoothing.

Data-reduction Summary

(1) A desk computer with digitizing attachment was programmed to accept fringe location and scaling factors directly from fringe photographs and to compute and print fringe order along with fringe location in actual specimen dimensions.

(2) The prepared enlargement of a 'data' moiré pattern

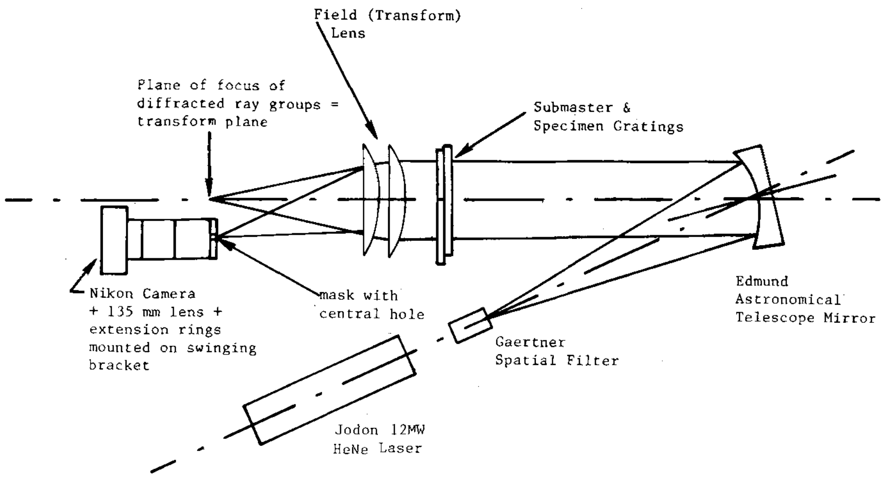

Fig. 6—Schematic of optical processing system for obtaining moiré-fringe photographs from specimen and submaster-grating photographs

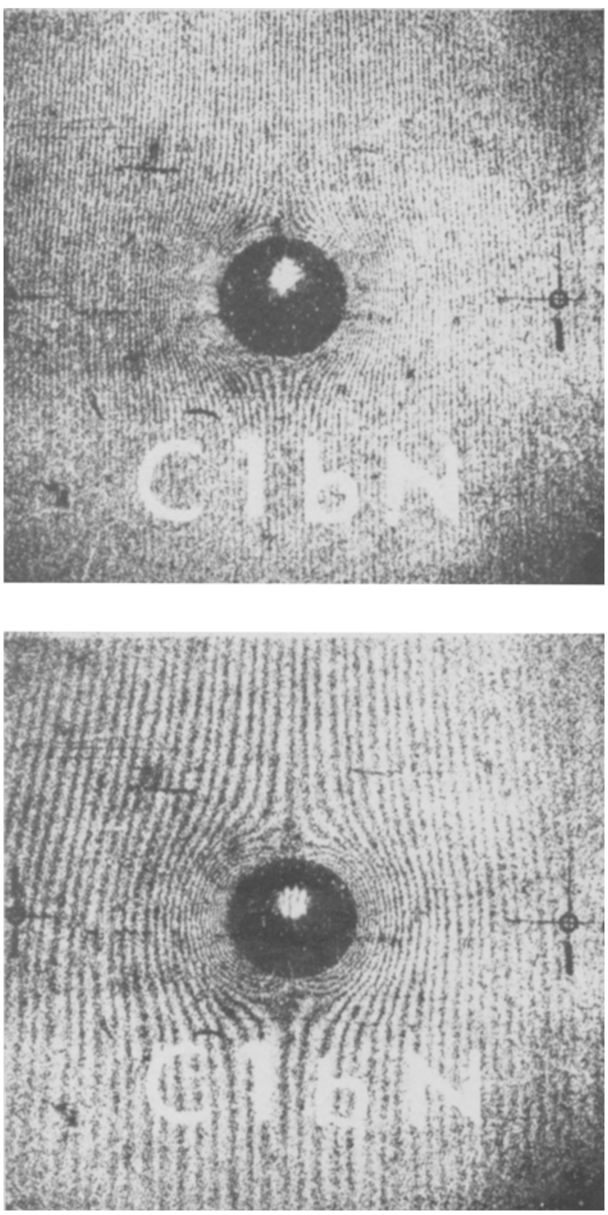

Fig. 7—Typical moiré-fringe photographs; sensitivity multiplication = 3, two values of pitch mismatch

was taped to the table of digitizer unit; fiducial mark locations and other data were entered as demanded by the program, and the locations of the intersections of the moiré fringes with the chosen axis were entered with the digitizer cursor.

(3) Step 2 was repeated for the matching 'baseline' fringe photograph.

(4) The fringe-location data were transferred manually to standard computer cards along with the data about specimen number, interference level, moiré sensitivity, and so on.

(5) A CDC 6300 digital computer with graphics facility was programmed to accept the moiré data and plot detailed graphs of the data input and to compute, print and plot displacement and strain as a function of distance from the hole edge.

(6) After detailed analysis of each data set, various summary and statistical analysis plots were generated using computer graphics.

Three computer programs for reducing data and plotting results were prepared. The first of these used spline functions in combination with least-squares curve fitting to compute and plot a detailed analysis of each set of moiré data and the resulting strain and displacement maps. The second routine utilized similar procedures to prepare a summary plot of all the data for each hole. The third program used data from the detailed analysis to construct individual and composite statistical summary plots for any or all the coldwork levels.

Typical Results

A composite statistical plot showing the distribution of average radial strain for each of the coldworking levels appears in Fig. 8. These plots, along with similar plots of tangential strain distribution, constitute the final product of the investigation. Discussion of the measured strain distributions, the implications of various aspects of the measurements, and comparisons with the measurements of Adler and Dupree[14] and Sharpe and his coworkers[10-12] is outside the scope of this paper. These details appear in a technical report,[1] and some are to appear in the technical literature. It is sufficient to point out here that comparisons with existing results are reasonable when properly interpreted. Variations of coldworking procedure are shown to be important, and the difficulty in measuring accurately the radial expansion can lead to errors in relating strain magnitudes to degree of coldworking.

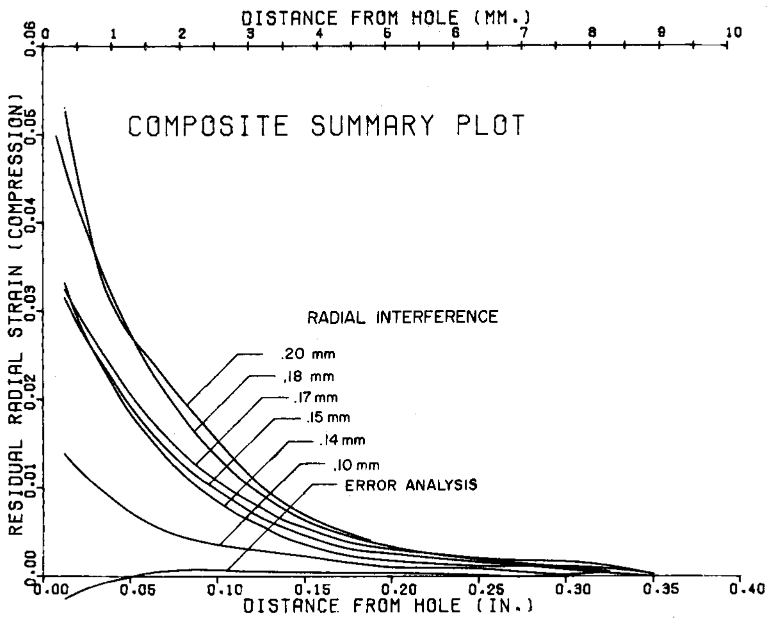

Fig. 8—Typical composite statistical summary plot showing average radial strains for each coldwork level

Acknowledgments

All the experimental phases and most of the data reduction were conducted at the Air Force Materials Laboratory, Wright-Patterson Air Force Base, USA, while the author was a senior resident research associate of the National Research Council. The remaining data reduction and writing took place at Imperial College of Science and Technology, London, England, while the author held a National Science Foundation Faculty fellowship. This support by NRC, AFML, NSF, and the generosity of Michigan State University in granting the necessary leave time, are acknowledged with gratitude.

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