Residual Stress Determination by Hole Drilling Combined with Optical Methods

D.V. Nelson

Abstract An overview is provided of the use of eight different optical methods with hole drilling to determine residual stresses. The methods considered are: brittle and photoelastic coatings, Moire interferometry, holographic interferometry, electronic speckle pattern interferometry, interferometric strain rosette, digital image correlation and shearography. A number of applications are summarized, such as the use of hole drilling with holographic interferometry to investigate stresses in rock structures accessed by deep boreholes and to determine manufacturing-induced residual stresses in fillets of small radii.

Keywords Hole drilling · Residual stress · Brittle coating · Photoelastic · Moire · Holographic · ESPI · Shearography · Interferometric · Rosette · Digital image correlation

Introduction

The hole drilling method using strain gage rosettes [1, 2] is a mainstay of residual stress determination and an ASTM test standard [3]. During the past six decades, eight different approaches have been explored for implementing hole drilling with optical methods instead of strain gages. The purpose of this paper is to review those approaches, which have been the subject of considerable research over the years, and which may offer opportunities for further development. It is hoped that this overview will also provide an interesting historical perspective, including examples of similar developments occurring independently at approximately the same time in different parts of the world, and in different engineering and scientific disciplines.

Brittle Coatings

The brittle coating technique appears to have been the first optical approach used with hole drilling [4], near the end of World War II, and at about the same time as the first use of strain gages with hole drilling [5–7]. A region of a component thought to contain residual stresses was coated with brittle lacquer. After hardening, a hole with a diameter of 1 to 3 mm was drilled through the coating and into the underlying material to a depth between 50 and 100% of the hole diameter. The release of residual stresses by the hole caused a pattern of cracking in the coating, with the characteristics of the pattern depending on the magnitude and state of stress. Typical patterns are shown schematically in Fig. 1. In order to reveal a pattern, it was often necessary to chill a part [4] or apply dye etchant [8] after drilling. Crazing (no prevailing direction of cracks) typically surrounded a cracking pattern. Empirical approaches for extracting quantitative information about residual stresses from the patterns were investigated [8, 9], while Durelli & Tsao [10] used the Kirsch solution [11] for stresses surrounding a through-hole to show that the magnitude of residual stresses should be approximately proportional to the square of the distance from the center of a hole to the beginning of a crazing zone. However, experimental uncertainties associated with the brittle coating technique, such as variations in coating thickness and sensitivity, made reliable quantitative determi-

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STRESSCOAT RESIDUAL STRESS PATTERNS

UNIAXIAL TENSION   UNIAXIAL COMPRESSION
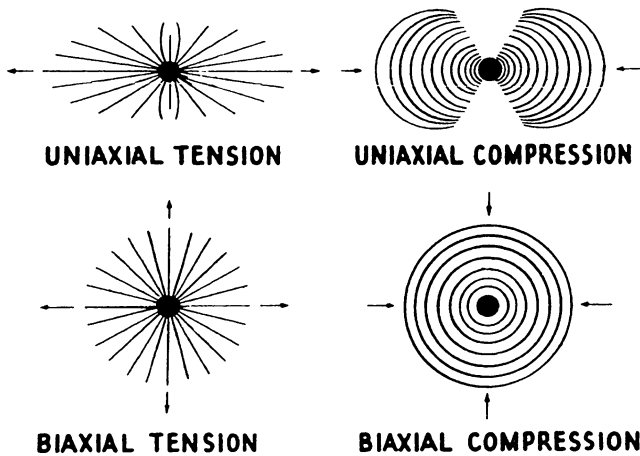
BIAXIAL TENSION   BIAXIAL COMPRESSION

Fig. 1 Schematic of cracking patterns in brittle coating after hole-drilling release of residual stresses [8]

nation of residual stresses a questionable proposition, and the approach appears to have been abandoned.

Photoelastic Coatings

When a hole is drilled through a photoelastic coating applied to material containing residual stresses, a pattern of isochromatic fringes appears, as illustrated in Fig. 2, when viewed with a reflection polarsicope. In 1960, Zandman [12] reported the use of hole drilling with a photoelastic coating as a means of revealing residual stresses in a weldment. Little detail on the approach was provided in that publication, though. Analytical relations to determine residual stresses from fringe orders measured at several locations around a hole were developed in the mid 1960s in Japan [13, 14] and experiments conducted using blind holes drilled to a depth of 100 to 120% of hole diameter. The relations were based on the Kirsch solution. It was found from experiments
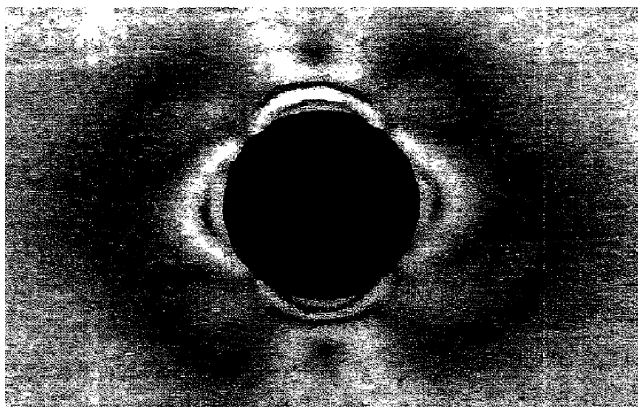

Fig. 2 Isochromatic fringe pattern in a photoelastic coating after hole-drilling into a plate experiencing uniaxial stress [14]

that the stresses were more dependent on coating thickness than expected from the analytical relations, which predicted that stresses would vary inversely with thickness, and empirical corrections to stresses were developed as a function of the ratio of coating thickness to hole radius. Also in the mid 1960s, and apparently unaware of the work in Japan, researchers in the Ukraine [15] reported analytical relations for determining residual stresses by the hole drilling-photoelastic coating method and application of the method to welded joints. In 1967, Gibbs et al. [16] published results of a 3D analysis of the surface displacements associated with the release of residual stresses by hole drilling in order to predict resulting fringe patterns in photoelastic coatings. The analysis was done using relaxation methods, and two cases were considered: (a) pure shear and (b) equibiaxial tension, since combinations of those two cases enabled solutions for other biaxial stress systems. During the 1970s, an analysis to account for a shear lag effect in the hole drilling-photoelastic coating method was developed [17], where shear lag refers to a diminution of strains transferred from the substrate through the coating thickness. Also in that decade, an automated experimental system for implementing the method was presented [18] and applied to finding residual stresses at welds. In 1990, Issa [19] reported an unusual application of the method—the determination of residual stresses in asbestos-cement pipes. The absorption of moisture by the pipe material caused tensile residual stresses that were believed to be a major contributor to cracking observed in service. To relieve residual stresses for measurement purposes, slitting was used rather than hole drilling. At the beginning of the current century, Cardenas-Garcia [20] presented a least squares, inverse problem analysis for the determination of residual stresses from fringe patterns in the hole drilling-photoelastic coating method using the Kirsch solution. More recently, Chang et al. [21] applied the method to determine uniaxial compressive stresses in a concrete specimen, using the Kirsch solution and digital image processing of isochromatic fringe data. In spite of developments over the past four decades, application of the method appears to be sporadic.

The hole drilling-photoelastic coating method is relatively inexpensive and does not require vibration stability as with interferometric approaches, but does have the drawback of requiring application of a photoelastic coating patch. In addition, software for determining stresses for blind holes, including how stresses vary with depth below a surface using incremental drilling, appears to be lacking.

Moire Interferometry

A representative set up for Moire interferometry is shown in Fig. 3. A cross-line grating is applied over a region of
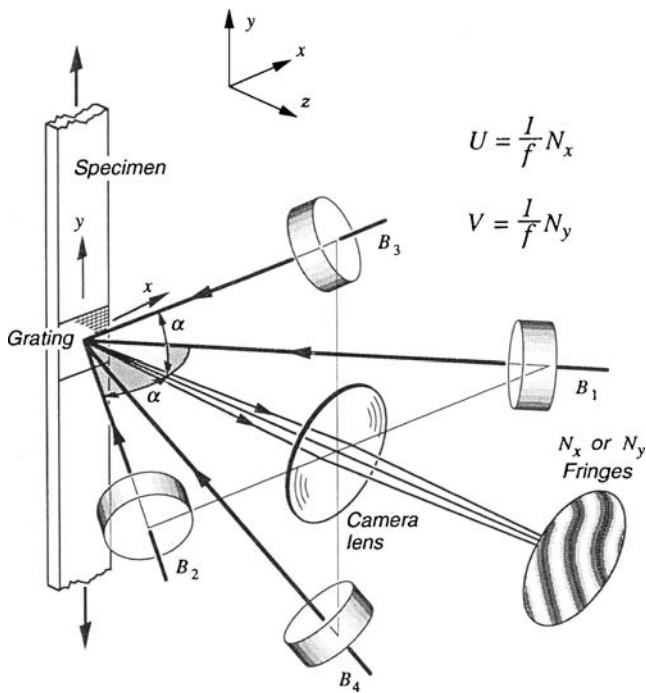
Fig. 3 An experimental set-up for Moire interferometry [22]

interest. Laser light beams B1 and B2 illuminate the grating, causing light to be diffracted in the z-direction. Deformation of the surface causes the diffracted beams to interfere in the image plane of a camera, producing a fringe pattern that can be related to U-displacements in the x-direction. Similarly, beams B3 and B4 form a fringe pattern related to V-displacements in the y- direction. Details concerning Moire interferometry can be found in Refs. [22] and [23].

In 1983, McDonach et al. [24] appears to have been the first to have applied Moire interferometry with hole drilling to reveal residual stresses, as shown by the fringe patterns (x-direction illumination) in Fig. 4. Residual stresses were
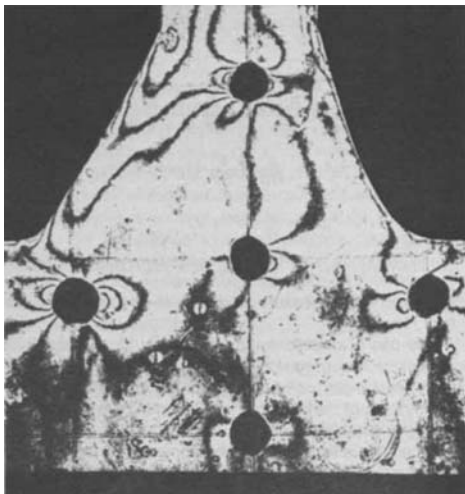

Fig. 4 Moire interferometric fringes for holes drilled in a T-butt weld cross section [24]

determined using displacement data obtained from the fringe patterns and relations between displacements and residual stresses similar in nature to those used for the strain rosette implementation of the hole drilling method. Later in that decade, and in the early 1990s, Nicoletto [25, 26] presented closed form relations to determine residual stresses from fringe patterns, while Furgiuele et al. [27] used a numerical approach for that purpose. In 1998, the Moire-hole drilling method was further advanced by a finite element based approach for determining how stresses vary with depth using incremental drilling [28], followed in 2000 by an approach combining Moire and Twyman-Green interferometry [29] to find stresses from the 3D displacements associated with the release of stresses by hole drilling. Representative Moire-hole drilling fringe patterns obtained with incremental drilling are shown in Fig. 5. In 2006, Min et al. [30] reported use of phase-shifting Moire interferometry with hole drilling to allow rapid determination of residual stresses with automated data processing, while Cardenas-Garcia & Preidikman [31] described a Moire-hole drilling method utilizing a finite element based, over-determined approach for finding stresses from a fringe pattern. Moire-hole drilling method has been applied to quantify residual stresses from various manufacturing processes such as grinding [32], laser welding [33] and shot peening [34]. It has also been applied in recent years to determine residual stresses in fiber reinforced composites [35–38], apparently more so than any other hole drilling-optical technique to date.

The Moire-hole drilling method enjoys the advantages of high sensitivity to small deformations, the existence of a computational methodology for blind holes and incremental drilling, commercially available equipment for implementation, and numerous successful applications. Drawbacks include the need to apply a grating on a smooth, flat surface and vibration isolation sufficient to enable interferometric fringe patterns to form and be recorded.

Holographic Interferometry

Holographic interferometry [39–44] appears to have been the first optical method applied with hole-drilling that did not require application of a coating or grating. Figure 6 depicts elements of a basic set-up for holography. A region of a test object is illuminated with coherent light, and an object wave is reflected towards a hologram location, which is also illuminated by a reference wave. The reflected object and reference light interfere to produce an intensity distribution. In classical double exposure holographic interferometry, a hologram of a test object is recorded by exposing a photographic plate to the object and reference light. Deformation of a surface region alters the path length
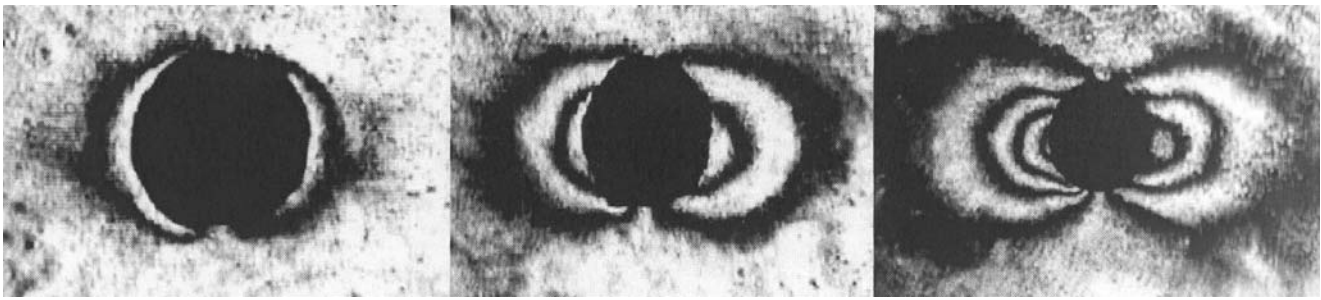
Fig. 5 Moire interferometric fringe patterns (U-displacement field) as a hole is deepened [33]

of light reflected from the object to the hologram. A second exposure of the plate is made. When the plate is developed and then illuminated by reference light, reconstruction occurs, with optical interference fringes appearing on an image of the object as viewed through the hologram. The resulting fringe pattern contains information on surface displacements. Photographic plates have, in many instances, been superseded by erasable and reusable thermoplastic recording plates [42]. Holographic interferometry can also be carried out in real time by recording and developing a hologram, them illuminating it with both reference light and reflected object light. Deformation of a surface of a test object will cause interference fringes to be observed in real time. Digital holographic interferometry [42, 44] may be implemented using a set-up similar to that in Fig. 6 except with a CCD array replacing a photographic plate. The intensity distribution in a hologram is recorded and stored digitally. After surface deformation occurs, a second hologram is recorded and stored. "Before" and "after" digital holograms can be reconstructed by multiplying each with a digital model of the reference light and computing the resulting diffraction field. Numerical reconstruction provides access to both in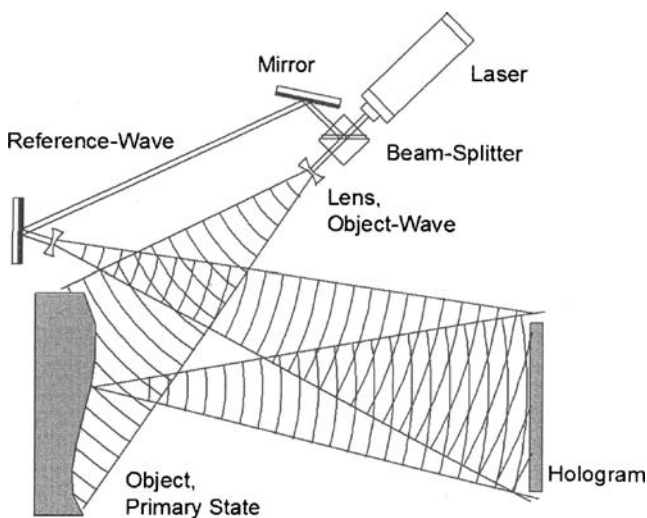tensity and phase information. The phase changes associated with surface deformation, including signs, can be determined directly from the "before" and "after" reconstructions without resort to intensity.

A typical fringe pattern from hole drilling combined with holographic interferometry is shown in Fig. 7. The pattern can be analyzed to obtain information about surface deformations from which residual stresses can be determined by computational means similar to those developed for Moire-hole drilling. The lack of symmetry from one side of the pattern to another in Fig. 7 is caused by the pattern responding to a mixture of in-plane and out-of-plane deformation, unlike Fig. 5, where the pattern responds to in-plane deformation only. Starting in the mid 1970s, work was underway at the Seismological Laboratory of Caltech to develop a holographic "stress-meter" that could be lowered into a borehole as depicted in Fig. 8(a) to determine stresses in subterranean rock. The stress-meter was designed to be locked in place in a borehole, then expose a photographic film to reference and object light, drill a hole into the borehole wall as in Fig. 8(b), make another exposure, and record the resulting optical interfer-

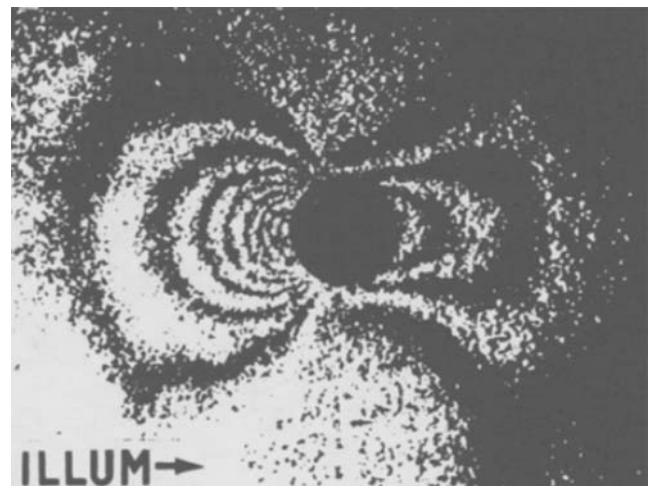

Fig. 6 Holographic interferometry set-up [42]

Fig. 7 Typical fringe pattern from holographic-hole drilling for uniaxial stress in the direction of illumination for a shallow angle between the surface and illumination direction. Pattern obtained with real time holographic interferometry, using a thermoplastic hologram plate
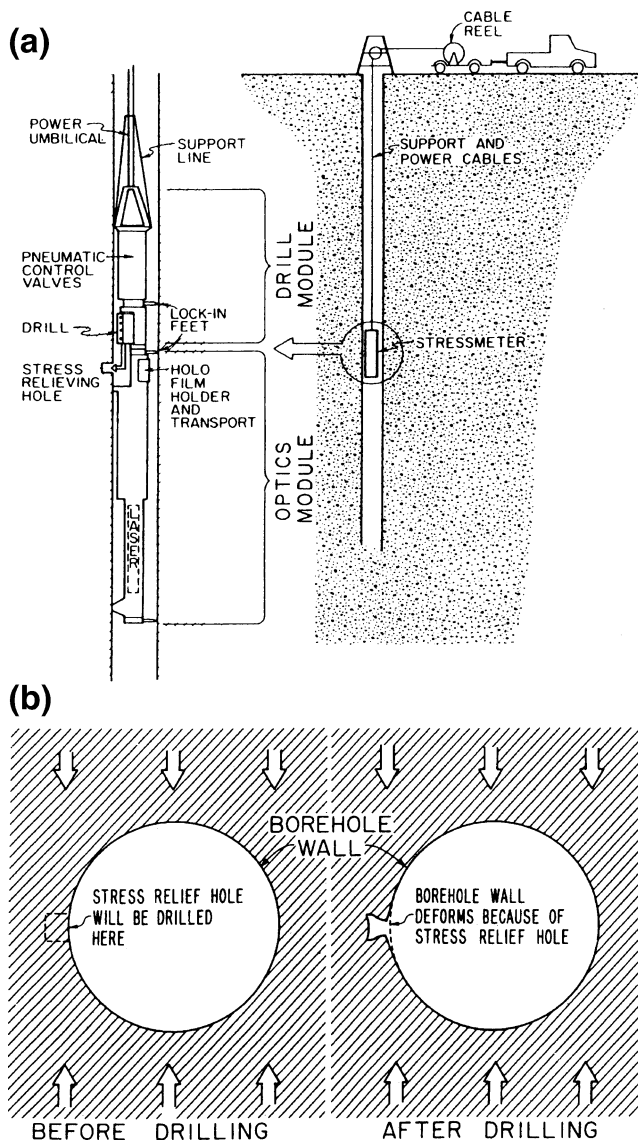
(a)

(b)

Fig. 8 (a) Schematic of holographic-hole drilling "stress-meter" in a borehole and (b) cross-section of borehole showing smaller hole drilled into a wall to release stresses [45]

fringe patterns that were then related to residual stresses using an approach based on the Kirsch solution. Meanwhile, and in the same era, a number of different researchers [47–49] in the former USSR were also independently developing different versions of a holographic-hole drilling method. In Ref. 47, for example, out-of-plane displacements associated with hole drilling were plotted vs. radial distance from a hole boundary along known principal residual stress directions. To find residual stresses, theoretically derived displacement curves for different assumed magnitudes of stresses were then compared with the experimental curves to see which provided good agreement. As another indication of world-wide interest in a holographic-hole drilling approach in that era, sandwich holography [39] was combined with hole drilling by researchers in China [50] to study residual stresses.

(a)

(b)
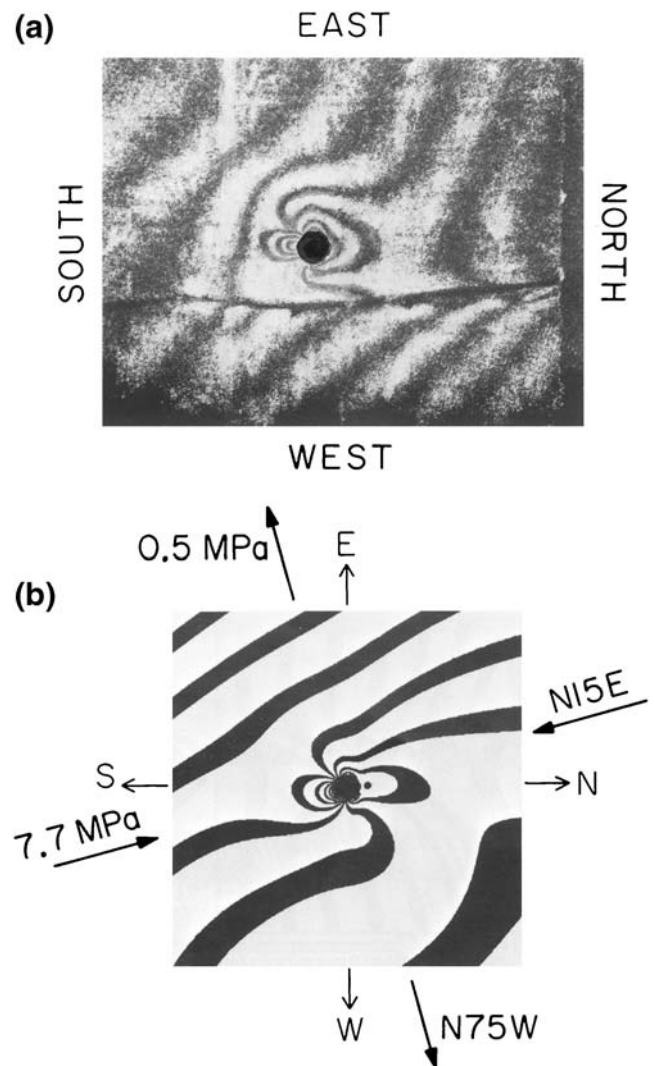
Fig. 9 (a) Fringe pattern observed in a horizontal borehole showing an existing crack near the drilled hole and (b) a computed fringe pattern that approximately matches features of fhe pattern in (a) with rigid body motion of the optics module taken into account [45]

ence fringe pattern on photographic film, which could later be retrieved for development. Results of this work were published in 1986 [45] in a geophysics journal. An observed fringe pattern is shown in Fig. 9(a), revealing fringes from release of stresses plus rigid body motion. To determine stresses, an analytical approach similar to the Kirsch solution was developed and used to generate synthetic fringe patterns for various assumed combinations of stresses and rigid body motions. The computed pattern that best matched an experimentally observed one was used to determine stresses. See Fig. 9(b). In the same era, independent work was taking place by the author and a collaborator from Newport Corporation to develop a holographic-hole drilling method [46]. Residual stresses were determined from radial displacements obtained from

The work cited above employed analytical relations such as the Kirsch solution to relate holographic-hole drilling fringe data to residual stresses. In the 1990s, a simple fringe counting approach was developed for determining residual stresses from a fringe pattern [51]. The approach used a finite element solution of displacements caused by hole drilling release of residual stresses assumed uniform with depth. At roughly the same time, an independent finite element based method for holographic-hole drilling was published [52] and later developed to enhance the determination from stresses from fringe patterns [53, 54]. In the mid 1990s, the holographic-hole drilling approach was extended to find stresses varying with depth by incremental drilling [55]. Application of holographic-hole drilling to determine residual stresses from shot peening was described [56]. Near the end of that decade, a portable holographic interferometer was used along with use of small scratches of rectangular or triangular cross section to release stresses [57, 58] and create fringes. The purpose of using scratches was to minimize the disruption associated with drilling holes.

Notable efforts to further develop the holographic-hole drilling method have continued in recent years. For instance, Lobanov & Pivtorak [59, 60] have described a compact, portable holographic system with a thermoplastic holocamera that could be installed on welded structures to find residual stresses by hole drilling. Pisarev et al. [61–63] performed comprehensive holographic-hole drilling studies of residual stresses in both thin and thick walled welded aluminum plates, and in tubular specimens. Different methods for analyzing the information contained in holographic-hole drilling fringe patterns continue to be pursued [64–66].

Similar to the Moire-hole drilling method, the holographic-hole drilling approach has the advantages of high sensitivity to small deformations, the existence of a computational methodology for blind holes and incremental drilling, commercially available equipment for implementation, and a record of successful applications. It has the additional advantage of being applicable to curved and rough surfaces. It also shares the drawback of requiring vibration isolation sufficient to enable interferometric fringe patterns to be observed and recorded.

ESPI

Electronic speckle pattern interferometry (ESPI) [40, 41, 67–70], also known as digital speckle pattern interferometry, and sometimes as TV holography, electro-optic holography or digital holography without waterfront reconstruction [42], can be carried out using a set-up similar to that shown in Fig. 6, except with the hologram plate replaced by a CCD array. Object and reference light superpose on the CCD to create a speckle interferogram that can be stored digitally. Fringes from object deformation can be generated numerically by digital subtraction (or addition) of "before" and "after" interferograms. To aid determination of phase changes associated with deformations, a set of several speckle interferograms taken with different phases of reference light can be obtained prior to and after deformation by phase stepping. The resulting stored intensity distributions can be processed with algorithms that yield phase changes caused by deformations. Other optical arrangements can be used instead, such as the one depicted in Fig. 10 for finding in-plane displacements in the x-direction.

ESPI with hole drilling was introduced in the late 1990s by Zhang and co-workers [70–73], including interesting applications such as determination of residual stresses in optical compact discs. An example of an ESPI-hole drilling fringe pattern is shown in Fig. 11. In the early part of this century, a number of finite element based methods for determining residual stresses from ESPI-hole drilling data appeared [74–76]. In 2003, a single beam ESPI hole drilling system and a full-field method for converting ESPI data to residual stress values were presented by Steinzig and Ponslet [77–79]. The system has become a commercially available product.

Development of the ESPI-hole drilling method continued with a study [80] showing an ability to determine residual stresses with errors typically less than 10%, while another study [81] found errors less than 8% and a minimum stress resolution of 10% of yield stress. A different study [82], though, had less favorable results, with errors between 4 and 37% and a mean of 19%. Methods that enable residual stresses to be determined from ESPI-hole drilling data in the presence of possible rigid body motions were described by Schajer & Steinzig [83] in 2005 and Dolinko & Kaufmann [84] in 2006. At about the same time, the machining of a 2 mm wide, stress-releasing groove instead of a hole was combined with ESPI to
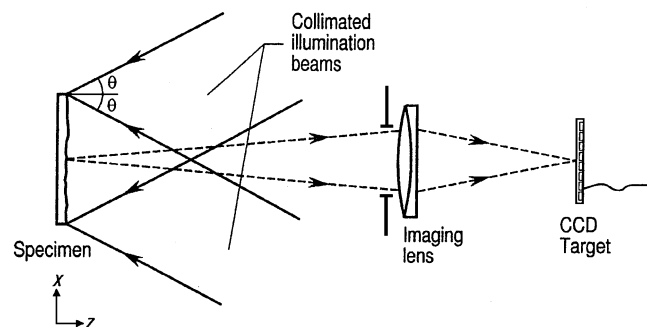

Fig. 10 Speckle interferometry set-up sensitive to in-plane displacements in x-direction [68]
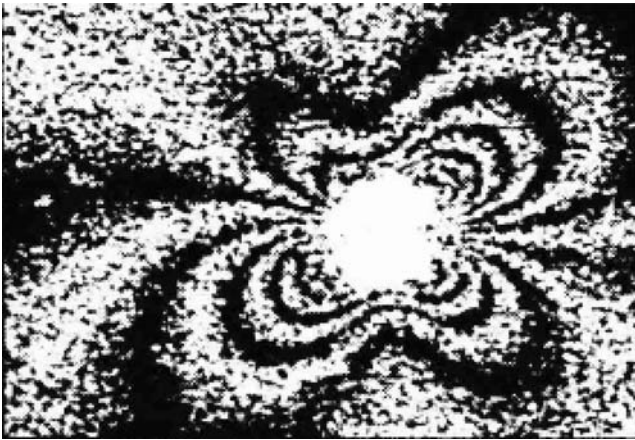
Fig. 11 A u-displacement sensitive fringe pattern found by ESPI-hole drilling with illumination in the x-direction (*horizontal*) and uniaxial stress applied at 45° to that direction [73]

explore the surface displacements created as the depth of the groove was increased incrementally [85].

In recent years, Viotti et al. [86] have described development of a compact, portable speckle interferometer with automated data processing. It provided promising experimental results when used for hole drilling determination of residual stresses. Albertazzi and co-workers [87–89] have described the evolution of another compact, portable interferometer, designed to be sensitive to radial in-plane displacements and able to make use of a laser diode as a light source, a significant advantage. It too has provided encouraging results in the hole drilling determination of residual stresses. An example of an application of that interferometer "in the field" is shown in Fig. 12. In 2009, Ribeiro et al. [90] reported the results of a comparative study of ESPI and Moire interferometric methods applied with hole drilling to find residual stresses. For both approaches, worst case discrepancies with known stresses were approximately 15%, with most discrepancies on the order of 5%. The advantages and drawbacks of the ESPI-hole drilling approach are similar to those mentioned previously for holographic-hole drilling.

Shearography

Unlike Moiré, holographic or electronic speckle pattern interferometry, shearography [91–94] produces fringe patterns that depend on displacement derivatives, rather than displacements. Shearography can be implemented with a photographic or thermoplastic plate, or digitally, which is more common today. A region of a test object is illuminated by coherent light. Referring to Fig. 13(a), light reflected from the surface of the region passes through a shearing device, which can be a Michelson interferometer with a slightly tilted mirror, for example. Light entering the interferometer is divided by a beam splitter and proceeds to the mirrors. Light reflected from the mirrors and emerging from the beam splitter forms a pair of laterally separated (sheared) images. As illustrated in Fig. 13(b), image shearing also causes light from two neighboring points $P(x,y)$ and $P(x+\Delta x, y)$ to meet on an image plane, producing optical interference and a speckle pattern. Phase shifting by piezoelectric-actuated translation of one of the mirrors can be used in automated determination of phase changes.

When the illuminated region deforms, path lengths of light rays scattered from the points $P(x,y)$ and $P(x+\Delta x, y)$ are altered, producing a phase change proportional to Δx and a term with displacement derivatives: $[A(\partial u/\partial x) + B(\partial v/\partial x) + C(\partial w/\partial x)]$, where A,B and C are sensitivity factors computed from the locations of the illumination source, recording device and a point on the test object. Image shearing can also be carried out so that shearing is parallel to the y-axis, with phase change then becoming a function of Δy and $[A(\partial u/\partial y) + B(\partial v/\partial y) + C(\partial w/\partial y)]$. Optical arrangements other than that in Fig. 13 are possible too, for example, a dual beam illumination setup similar to that in Fig. 10, which can be used for finding in-plane strains by shearography [93].

In the mid 1990s, the use of shearography combined with hole drilling was described by Hung et al. [95] based on the Kirsch solution. An example of a shearographic-hole drilling fringe pattern is shown in Fig. 14. At about the

Fig. 12 Radial, in-plane speckle interferometer-hole drilling device being used to measure the stresses in a pipe induced by ground movement [89]
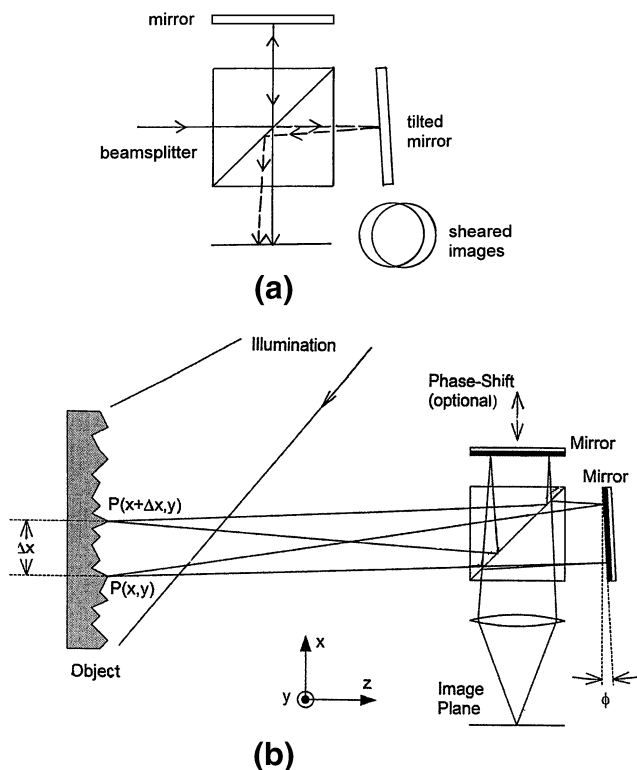
Fig. 13 (a) modified Michelson interferometer and (b) an optical set-up for shearography [42]

same time, Wu & Qin [96] presented promising experimental results of applying shearographic-hole drilling to determine both uniaxial and biaxial residual stresses, also using the Kirsch solution. They noted a publication by other researchers in the *J. Experimental Mechanics* (a Chinese language journal) that apparently described the use of shearing speckle interferometry with hole drilling as early as the mid 1980s. More recently, Montay et al. [97] have demonstrated a technique in which a grating was
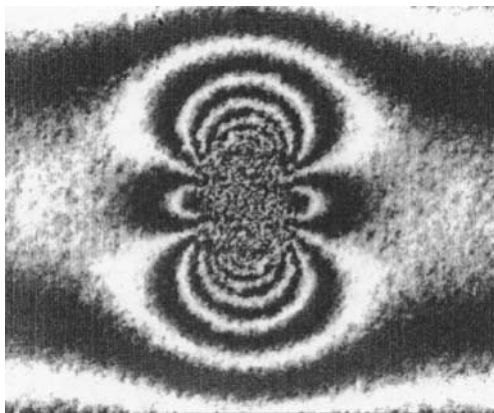

Fig. 14 Fringe pattern from shearographic-hole drilling for uniaxial tensile stress [95]

applied to a surface region and combined with a shearography to determine the strain field from incremental hole drilling, enabling residual stresses vs. depth from shot peening to be found. The technique was found to be less sensitive to vibration than Moire interferometry.

Shearography-hole drilling has the advantages of being a non-contacting method (when implemented without a grating) and having substantially reduced sensitivity to vibration [91, 93] relative to Moire, holographic or ESPI-hole drilling. On the other hand, it does not seem to have been developed or applied to the extent of those other interferometric methods. For instance, a computational methodology and experimental evaluation for blind holes or incremental drilling do not appear to have been reported (except for the case of grating shearography).

Interferometric Rosette

An interferometric strain rosette (ISR) [98] is formed by indenting the surface with a micro-hardness tester using a six- or eight-faced indenter, producing a triangular configuration as shown in Fig. 15 for a 60° rosette. Each pair of indentations acts as a miniature strain gage in the direction of a line joining the pair. If the indentations are sufficiently small, shallow and closely spaced, illumination with laser light causes diffraction in the reflecting directions from the faces in each indentation. The light diffracted from the pairs of indentations interferes to create a fringe pattern such as that shown in Fig. 15. An ISR allows three normal strains in the directions between pairs of indentations to be found by analyzing changes in the interference pattern when surface deformations occur.

In 1997, Li [99] reported a method of residual stress determination in which an ISR was formed near a location where a hole was to be drilled. The surface displacements resulting from release of residual stresses by hole drilling caused changes in the interferometric fringe pattern that were analyzed to find strains and corresponding residual stresses, based on the Kirsch solution. The method was extended [100] with finite element modeling to the determination of the profile of shot peening residual stresses vs. depth using incremental hole drilling in conjunction with three in-plane strain components and two out-of-plane slopes found from ISR data. Later, the method was applied with incremental ring coring (trepanning) to find stresses vs. depth [101]. The tiny footprint of the interferometric rosette, as seen in Fig. 15, enables application to measurement locations inaccessible to conventional strain rosettes, which is a significant advantage of the method. Another advantage is that fringe patterns are unaffected by rigid body motions [99]. The computational methodology to enable applica-
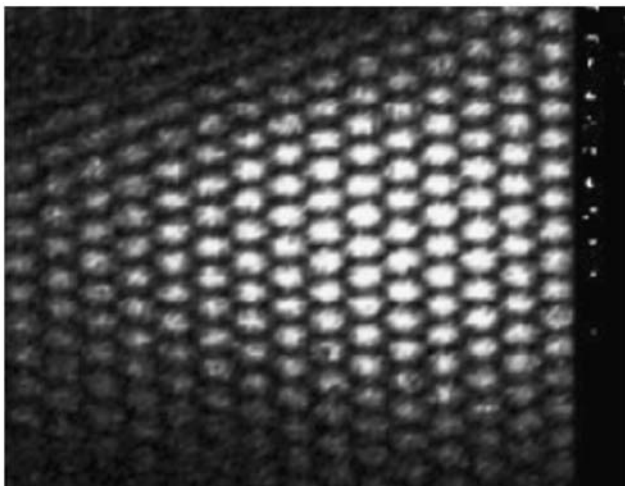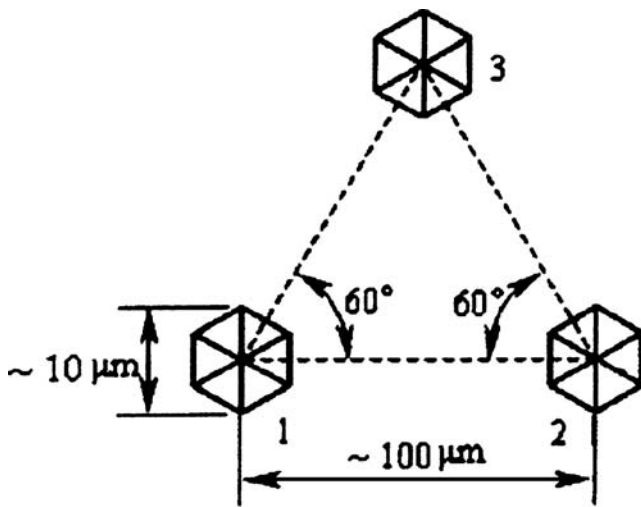
Fig. 15 Interferometric strain rosette and a typical interference fringe pattern [99, 100]

tion of the method for blind holes and incremental drilling exists, and the approach has been applied successfully to find residual stresses for ultrasonic spot welds, laser welds, shot peening, etc. As with the other interferometric methods in this review, vibration stability sufficient to allow formation and capture of a fringe pattern is needed.

Digital Image Correlation

In 3D digital image correlation (DIC) [102–104], a surface region is illuminated with ordinary white light and viewed with a pair of high resolution CCD cameras, as illustrated in Fig. 16. (One camera can be used for 2D measurements). Reference images of the surface are captured and digitized prior to deformation. Sub-sets of an image (typically a square of about 10 to 20 pixels on each side) are defined. By comparing the locations of corresponding subsets in images taken by two cameras, 3D coordinates of the surface can be determined.

Fig. 16 Digital image correlation set-up for measurement of tire deformations showing two cameras and lamps [105]

After deformation, 3D displacements can be found by tracking the movement of corresponding sub-sets between reference images and images taken after deformation.

In the middle of the current decade, the use of hole drilling combined with DIC to determine residual stresses was explored independently by civil engineering researchers [106] and mechanical engineering researchers [107] at the same time. DIC allowed displacements from hole drilling to be found and related to residual stresses using computational methods similar to those developed earlier for the interferometric approaches reviewed here. In 2008, Lord et al. [108] extended DIC-hole drilling to enable the determination of profiles of residual stresses from shot peening vs. depth using incremental drilling, with results shown in Fig. 17, where the stress profiles found by DIC-hole drilling agree reasonably well those determined by
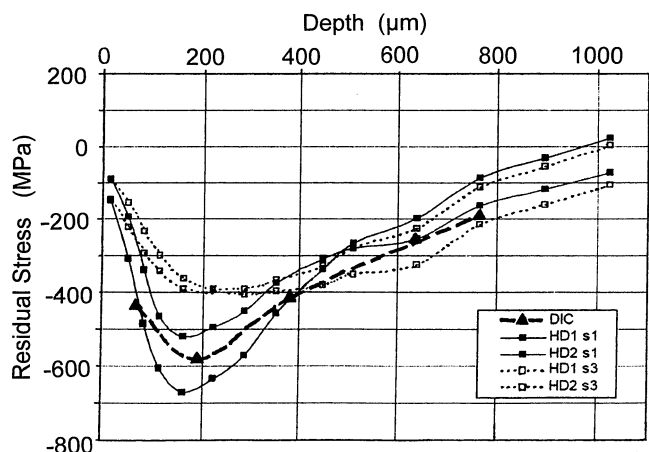

Fig. 17 Comparison of shot peening residual stresses determined by digital image correlation (DIC) and hole drilling with strain gages (HD) [108]. Principal stresses are denoted by s1 and s3

hole drilling with strain gages. (The difference between principal stresses s1 and s3 determined with strain gages was unexpected.) In 2009, Gao & Shang [109] described a new approach for determining residual stresses by DIC-hole drilling that takes knowledge of the hole drilling deformation field for an assumed set of residual stress components (σ_x, σ_y, τ_{xy}) and incorporates that knowledge in an algorithm that performs image correlation, instead of finding displacements with "general purpose" image correlation software, then solving for residual stresses in terms of displacements found.

The DIC-hole drilling approach has the advantages of ordinary white light illumination, a more direct determination of displacements than by optical methods based on phase changes, applicability to rough or curved surfaces, commercially available equipment and software to implement DIC, no interferometric vibration stability needed, and an ability to correct for rigid body motions. In tests conducted by the author and colleagues, it was possible to record a set of images by DIC, then remove the test object for hole drilling at another location, then return the specimen to approximately the same initial location for recording of a set of "post- drilling" images. Drawbacks of the approach are the need to perform camera calibrations prior to capturing

images and approximately a factor of ten less sensitivity to deformations than ESPI or similar interferometric techniques [104]. In spite of the lower sensitivity, it appears possible to obtain reasonably accurate results with DIC-hole drilling based on published studies to date.

A form of DIC-hole drilling has recently appeared in the field of micromechanical devices. In 2007, Sabate et al. [110] described the use of hole drilling method with DIC to determine residual stresses in thin films using a hole of only 4.5 μm diameter. The hole was created by focused ion beam milling, and DIC was implemented with scanning electron microscope imaging. This work was done in Europe by micro-systems researchers with backgrounds mainly in physics, at about the same time and seemingly unaware of the other approaches summarized in this paper. An example of the displacement field found by micro-hole drilling is shown in Fig. 18, where the irregular displacement contours may reflect experimental uncertainties in measurements, or perhaps non-homogeneous material behavior at the micro-scale. The use of micro-holes with digital image correlation appears to have followed the initial use of micro-slots for stress release [111, 112].

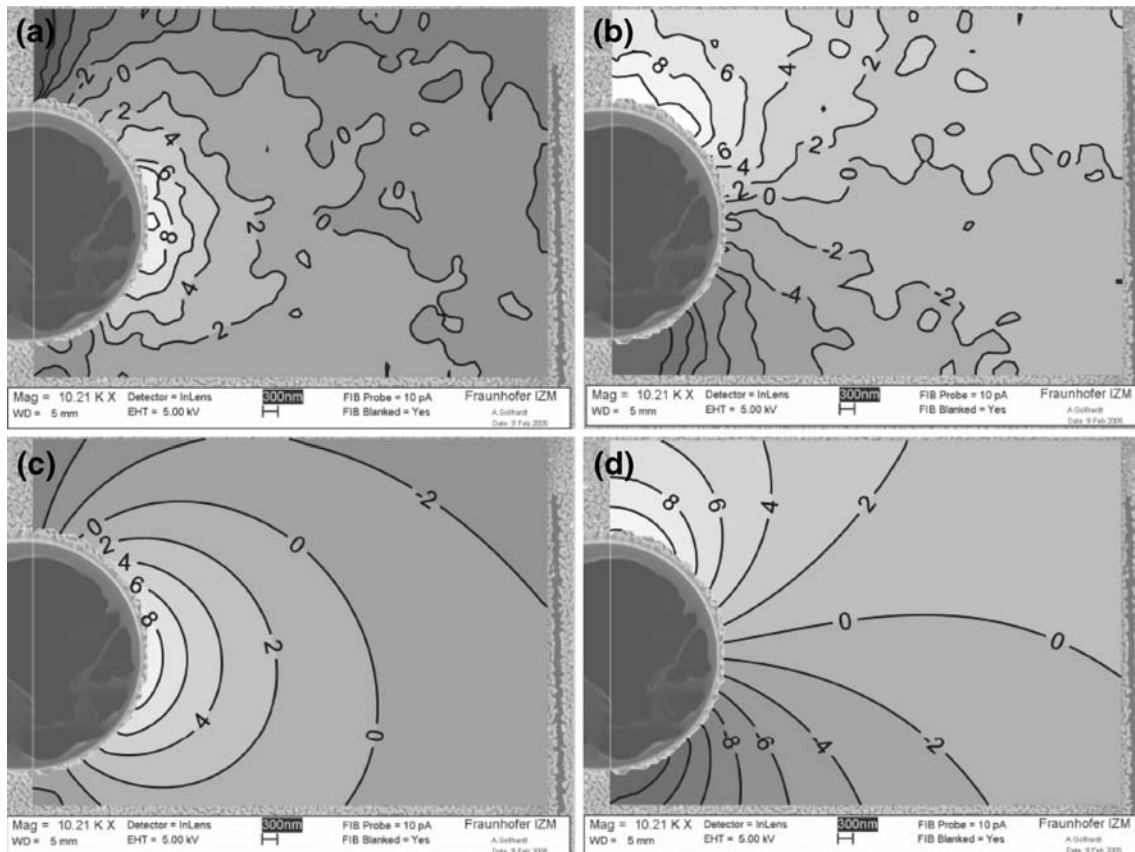An optical-hole drilling method has even found recent use in tissue mechanics. Micro-holes have been created in

Fig. 18 Displacements in (a) horizontal direction (u_x) and (b) vertical direction (u_y), with analytical fits (c) and (d) to the data [110]. Displacements in units of nm. (© IEEE)

thin biological tissue layers by ablative laser pulses. The resulting viscoelastic displacement vs. time recoil behavior associated with release of stresses has been studied with scanning confocal microscopy and a form of digital image processing [113], with the authors noting that their experiments were "inspired by hole drilling methods for evaluating residual stresses." Relations between residual stresses and relaxed strains for hole drilling of isotropic engineering materials from Ref. [114] were used to gain insights into the experimental behavior observed. The authors were well aware, though, of the limits of applicability of those relations to biological material.

Discussion

The development of numerous optical approaches for use with hole drilling may be considered evidence of the technological significance of the hole drilling method as a means for determining residual stresses. The amount of effort that has been devoted to developing the approaches is reflected in part by the lengthy reference list in this review.

A significant potential advantage of optical approaches is extension of the hole drilling method to regions that would be difficult to access with strain gages. For instance, Fig. 19 shows a holographic-hole drilling fringe pattern for a hole that was drilled into a small radius, undercut fillet of a diesel engine crankshaft. By creating a finite element model of the fillet geometry and by accounting for the

Fig. 19 Holographic-hole drilling fringe pattern viewed looking into a rolled, undercut fillet in a crankshaft, with illumination directed parallel to the fillet. The hole was 0.8 mm in diameter and 0.3 mm deep, drilled in the center of a fillet with a radius of 2 mm [115]

effect of fillet surface curvature on the observed fringe pattern, it was possible to perform incremental hole drilling to determine the profile of residual stresses vs. depth induced by rolling of the fillet [115]. Other optical approaches such as ESPI, shearography, digital image correlation and interferometric strain rosettes, could potentially be applied in such situations as well.

It should be noted that the vibration stability needed for high sensitivity interferometric approaches has tended to hamper use outside of laboratory environments. However, portable interferometric systems (e.g, ESPI) that can be deployed in the field have been demonstrated recently and may experience increased use. The initial results of DIC-hole drilling, a non-interferometric approach, are sufficiently encouraging that development of a portable system for use outside of the laboratory seems a realistic prospect, especially with likely continued improvements in displacement resolution capabilities of digital image correlation.

The photoelastic coating-hole drilling technique has been used intermittently over the years, but it may be worth revisiting with available modern automated photoelastic equipment and finite element modeling to see if it might warrant further development. Applying a small photoelastic coating patch to a region of interest is relatively easy and reflection photoelasticity has a lengthy record of successful use in lab testing and manufacturing environments.

The review in this paper has provided examples that if one individual or group is exploring a new approach, it is quite likely that others, perhaps in different parts of the world, and in some cases even working in different disciplines, are independently exploring a similar approach at approximately the same time, often unaware of each other's efforts. The review has also has found that the use of hole drilling method extends beyond mechanical or materials engineering to disciplines such as physics, geophysics and biomechanics, further evidence of the notable role of the hole drilling method in experimental stress analysis.
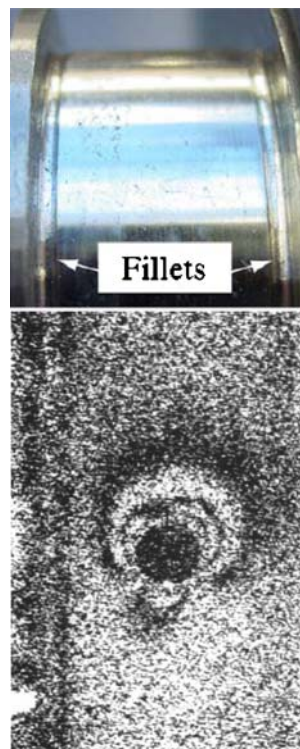
Summary

Starting with brittle coatings more than sixty years ago, researchers have been investigating optical approaches for use with the hole drilling method of residual stress determination. Approaches to date have employed most, if not all, of the major optical methods used in experimental mechanics, including brittle coatings, photoelastic coatings, Moire interferometry, holographic interferometry, interferometric strain rosettes, electronic speckle pattern interferometry, shearography, and digital image correlation. Compact, portable optical-hole drilling systems have appeared in recent years and further development is ongoing.

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