FEATURE *Technology Application Series*
by M. Steinzig and T. Takahashi

RESIDUAL STRESS MEASUREMENT USING THE HOLE DRILLING METHOD AND LASER SPECKLE INTERFEROMETRY PART IV: MEASUREMENT ACCURACY

In parts I, II, and III of this series we described how an electronic speckle pattern interferometer could be configured to make residual stress measurements. In the last installment of the series, we will describe efforts to validate the accuracy of the system in metallic samples with known states of stress.

The depth and diameter of the drilled hole are inputs to the calculation of the stress, and the ability to control these parameters affects the overall accuracy of the technique, as previously described in Section III. The system described here makes use of an automated drilling system to eliminate measurement of depth and diameter after each hole has been drilled, and minimizes variability caused by the operator in drilling the hole. The drill is mounted on a computer-controlled motorized stage, and the depth of the hole is input into the system software. The software drives the stage and drill toward the part until electrical contact is made between the part and the drill bit. This signals the start of the hole, and the stage continues to move the drill forward until the specified depth of the hole is reached.

In a series of tests, this system produced holes that were within 20 microns of the expected depth in the worst case, with an average depth within 5–10 microns of the expected depth. Diameters of the drilled holes are also accurate within 10 microns, although both the hole depth and diameter are less accurate if the drill is not set up perpendicularly to the part surface.

ACCURACY VALIDATION

Determining the accuracy of residual stress measurement techniques first requires preparing samples to make measurements. Our criteria for samples include the ability to “know” the state of stress a priori, a minimal stress with depth gradient, the ability to make multiple measurements in a single sample, and the ability to easily produce samples. To meet these criteria, we have developed two types of specimens with induced stresses. The first of these is an interference fit ring and plug, which has equi-biaxial stress in the plug, and tensile and compressive stresses in the ring. The second is a simple 4-point bend test fixture, which can be used with any type of material as a sample.

ET occasionally features short Industry/Application articles under the title, “Technology Applications.” The short articles demonstrate real world application of both measurement techniques and apparatus to be used primarily in industry and, in some cases, the classroom. This month we are continuing “Dynamic Strain Measurement Using Advanced 3D Photogrammetry.” Please contact Series Editor, Dr. Kristin B. Zimmerman, at kristin.b.zimmerman@gm.com, if you are interested in submitting a Technology Applications article.

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RING AND PLUG SAMPLE

The 12 mm thick 2024-T351 aluminum ring (100 mm outer diameter (o.d.) and plug (50 mm o.d.) provide good samples in which to measure various states of stress, with drilling occurring in the 12 mm dimension. The plug is cooled in liquid Nitrogen, and inserted in the 50 mm (nominal) hole in the ring (total diametrical interference of 0.08 mm), inducing stress as the assembly returns to ambient temperature. More details on the preparation of this sample have been described previously.[1] Based on the radial strains measured by a 10-element gage located on the ring prior to assembly, the sample used for this test was expected to have 56.9 MPa of equi-biaxial compression in the plug. Plug and ring calculated stresses are shown as green solid lines in the graphs of Figure 1.

Prior to drilling in the assembled plug, several measurements using the ESPI system were made in the as-received aluminum (1/16″ holes drilled to a depth of 0.48 mm). An average as-received stress of 19.4 MPa in the rolling direction and 4.9 MPa in the transverse direction resulted. The system was then set up to make measurements in the ring and plug assembly. The drilling and holography systems remained stationary during these tests, and the sample was rotated about the plug center in a clamping fixture. Using this setup, 11 measurements were made in the plug at a distance of 25.4 mm from the plug center, and 44 mm in the ring (4 series of 11 holes, at 29.2, 32.1, 35.7 and 41.1 mm from the plug center, respectively), using a 1.59mm (1/16″) diameter drill bit to a depth of 0.48 mm. The initial hole for each series was drilled with the rolling direction oriented vertically (0°), and a clockwise rotation of approximately 30° between each subsequent measurement.

The graph for the plug shows the raw horizontal and vertical stresses (dashed red and blue lines) as a function of the angle between the horizontal and the rolling direction. After adjusting for the as-received stresses, the measured stresses in the plug (solid red and blue lines) fit well with the calculated value of 56.9 MPa. The average of the 11 measured stresses in the plug are −54.7 MPa in the horizontal direction and −53.9 MPa in the vertical direction, with a standard deviation of 2.7 and 2.0 MPa, respectively. In the ring, the average measured results compare well with the calculated values, but the variation of answers is larger in the ring than in the plug, with a maximum standard deviation of 8 MPa for a given series of holes.

The results shown in Fig. 1 were generated using the new least squares analysis technique. The plug data was re-analyzed using the triad method previously used for analysis, and described in Section II of this series. The graph in

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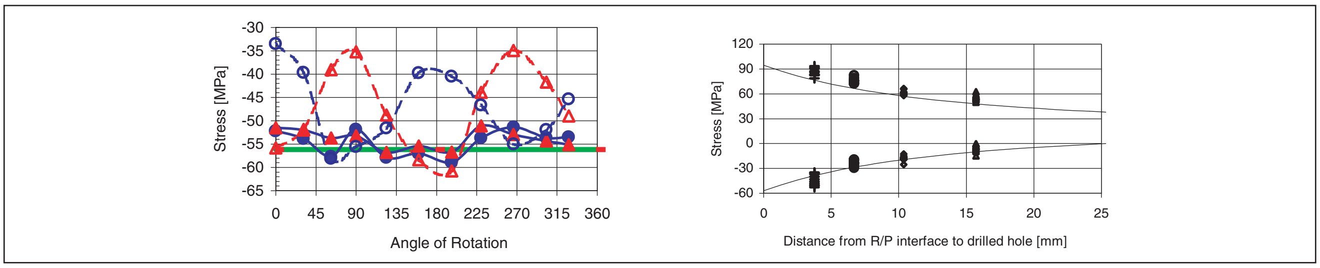

Fig. 1: Measured and calculated stress results in plug (left graph, with blue and red representing stresses in the vertical and horizontal directions, respectively) and ring (right graph, with top and bottom data points showing tangential and radial stresses, respectively) of the assembly

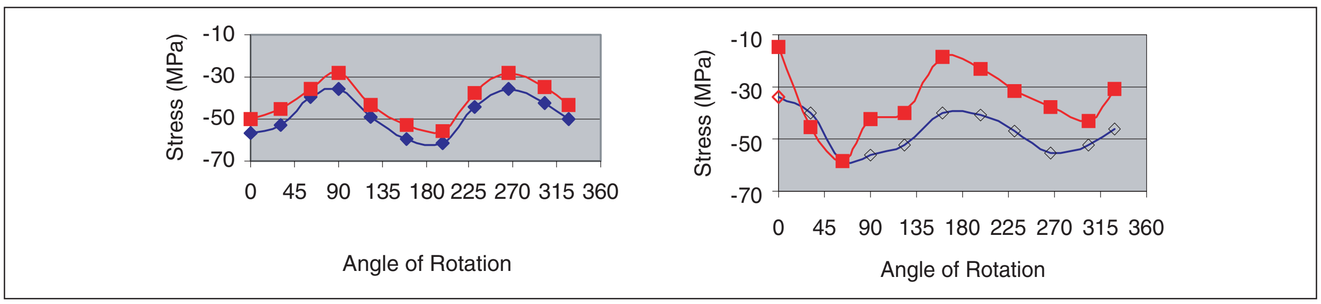

Fig. 2: Comparison between least squares analysis (blue) and triad analysis (red), for horizontal stress (left graph) and vertical stress (right graph)

Figure 2 shows the comparison of results between the triad method and the new least squares analysis technique.

The difference in the two analyses is a fixed offset in the horizontal stress (left graph of Fig. 2), with the triad analysis (red curve) resulting in approximately 5 MPa lower magnitude of stress. The difference in the two analysis techniques is more significant for the vertical axis of stress (right graph) where the offset is not fixed, and is over 20 MPa for some data points. In each case, the new analysis improves the accuracy of the overall technique.

BEND TEST FIXTURE

A four-point bend test fixture was adapted from Yerman[2] to be used with the ESPI system. This fixture has the advantage that samples can be inexpensively produced, and multiple holes drilled in the 12.7 cm between the two inner pins. Although there is nominally only a single axis of stress produced by bending the sample, and a slight gradient with depth occurs, this setup provides an ideal venue for studying accuracy and repeatability of the ESPI hole drilling technique. The samples are measured with the bend axis horizontal in the view of the imaging system, as shown in Figure 3. The side of the sample in tension is measured by the system.

The consideration of inducing stress by the drilling technique means that a study of the accuracy of measured results as a function of drilling speed and feed rate might be important. This type of testing requires that multiple measurements be made in the same sample that contains a known state of stress. These criteria are met by the bend test fixture.

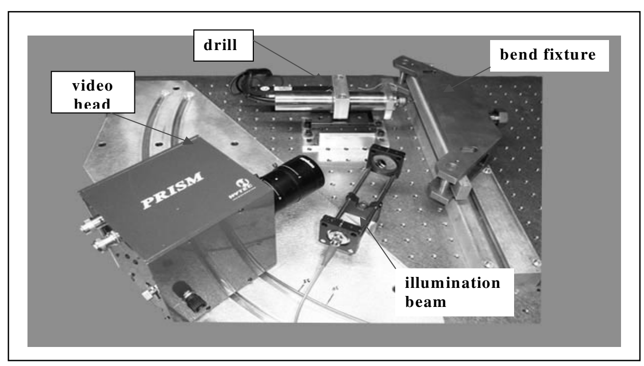

Fig. 3: Sample set up in bend test fixture, showing arrangement of drill, video head and illumination beam

Aluminum Samples

In aluminum 7075-T651 samples, (25.4 mm wide and 4.3 mm thick) feed, speed and bit type were all varied in a series of controlled tests. It was found that for aluminum, the results were not particularly sensitive to these parameters.[3] Accurate, repeatable results have been obtained using 15,000 rpm, 0.05 mm/s feed rate, and a 1/16″ two-flute end mill. The results reported for aluminum are all for 0.5 mm depth holes. No significant as-received stresses (<15 MPa) were measured with any consistency in the aluminum samples. Stresses are reported in the bending (horizontal) and transverse (vertical) directions. Shear stress results were near zero and have not been shown for clarity.

The results in Fig. 4 are from a 7075 aluminum sample, in which 9 measurements were made with the sample bent to

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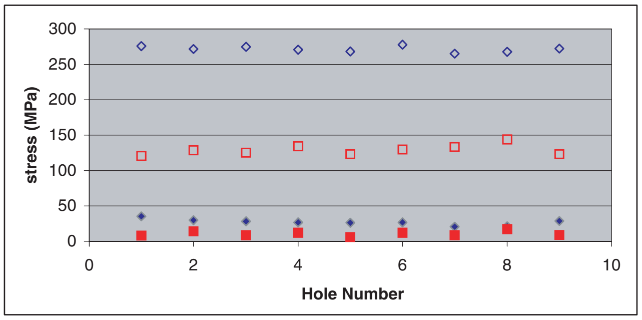

Fig. 4: Bending (open symbols) and transverse (closed symbols) measured results, for applied bending stresses of 117 and 234 MPa

3.81 mm of centerline deflection (expected bending stress of 117 MPa) and 9 additional measurements made with the same sample bent to twice the deflection (7.62 mm, expected bending stress of 234 MPa). The primary purpose of this test was to see if the increase in measured stress was linear with deflection. The average values of the measured stresses shown in Fig. 5 are 129 and 272 MPa respectively, representing a 47% increase in stress level. In the transverse direction, we expect a small but non-zero induced stress because of the finite depth of the part. The transverse stresses measured 11.9 and 27.3 MPa for the smaller and larger bending, respectively, or a 44% increase in stress. In this case, the deflection was measured with a relatively crude setup, using a dial gage indicator mounted to a comparator stand. In the rest of the samples discussed here, greater care was taken in measurement of deflection.

Figure 5 shows the results from two samples, both bent to have 235 MPa of bending stress at the surface of the beam. The left graph shows the results of three series of holes drilled in a single beam specimen. The first six holes were drilled 8 mm from one edge, the middle six holes drilled along the centerline of the specimen, and the last six holes 8 mm from the remaining edge. The transverse stress is noticeably different in the six holes drilled in the middle of the sample, which is to be expected in a sample of this thickness. The right graph is a series of 17 holes drilled in a beam, with half the holes drilled along one edge and half along the other edge. We notice a slightly higher value of transverse stress than in the first sample, but reasonable comparison in the bending stress, with the average of the left and right graphs 250 ± 14 and 237 ± 18 MPa, respectively. (The error band is reported as ±2 times the standard deviation). For our purposes, the "error" is defined as the difference in the expected stress and the measured average stress, divided by the measured average stress. The error shown in the left and right graphs are 6% and 1%, respectively. In these results, we have not tried to account for the stress gradient as a function of depth, because it is a relatively small effect. The bottom of a 0.5 mm deep hole would be expected to have a stress 17% lower than at the surface, meaning that the arithmetic average over the depth of the hole would be 8.5%. The actual effect is even less than that, because the deformation that occurs for material removed near the surface is weighted higher than for material removed near the bottom of the hole.

Steel Samples

Results from two different steels are reported. All the tests in these samples were performed at rotational speeds of 40,000 rpm, 0.05 mm/s feed rate, using a two-flute end mill, with hole depths of 0.5 mm, and samples 25.4 mm wide and 12.8 mm thick. Prior to bending the sample in the fixture, measurements were made in the as-received state, and used to adjust the final answers after bending measurements were made. As with the aluminum samples, shear stresses are not reported for clarity in the graphs.

HR 1016 Steel Samples

A test was performed using hot rolled 1016 steel bar, with an average as-received measured stress of 4.8 MPa in what would become the bending direction. In the transverse direction, the average as-received measured stress was −5.1 MPa. After testing in the as-received state, the sample was bent in the fixture to a centerline deflection of 1.17 mm, to induce a stress of 207 MPa in the bending direction. The measured results from 12 holes drilled 8 mm from the edge of a sample are shown in Fig. 6.

The average measured stress in the bending direction is 203 ± 19 MPa, and an average stress in the transverse direction is 3 ± 16 MPa. After correcting for the as-received stress measurements, the final results are 198 MPa in the bending direction, and −1 MPa in the transverse direction, which gives an error for the bending stress of −5%.

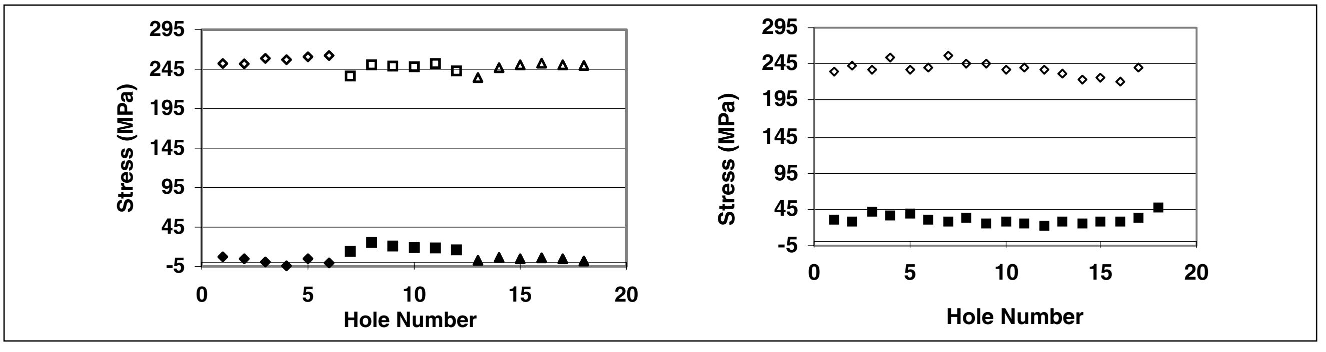

Fig. 5: Bending (open symbols) and transverse (closed symbols) measured results from 4 point bend test fixture, 2 different samples

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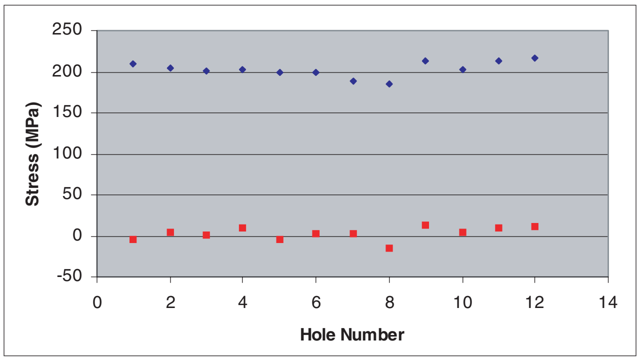

Fig. 6: Results in 1016 hot rolled steel; sample prepared to have 207 MPa of tension in the bending direction. Blue points are stress in the bending direction, red points are in the transverse direction.

Bead Blasted Steel

A series of tests were performed in AI 206 steel that had been bead blasted in preparation for painting, and then stress relieved by furnace heating. The actual state of stress in this material was not known a priori, but it is expected that the stress with depth profile would be similar to that of a shot-peened part. The primary purpose of this test was to verify overall accuracy of the measurement technique in a steel sample, but in this case we will also see if the bending stress could still be accurately measured when superimposed over a significant stress existing in the base material.

Four sets of data were taken in the as-received sample, comprising four holes at each of the depths 0.05, 0.1, 0.3, and 0.5 mm. The averages of the four results at each depth are shown in the table and plot of Fig. 7, and qualitatively show the expected trend for a bead-blasted part. It should be noted that the single-depth hole-drilling technique weights the stresses near the surface more heavily than those stresses at the bottom of the hole. However, we report these results so the effect of the applied bending stress can be taken in context.

The same sample was then bent to induce a stress of 207 MPa, and two sets of measurements were made at 0.3 mm and 0.5 mm depth (12 holes at each depth) as graphed in Figure 8.

The average stresses for the 0.3 mm depth holes were 115 ± 12 and –84 ± 15 MPa in the bending and transverse directions, respectively. Adjusting for the as-received stresses, the final results are 194 MPa in the bending direction, and 28 MPa in the transverse direction. For the 0.5 mm depth holes, the average stresses were 142 ± 8 and −53 ± 12 MPa in the bending and transverse directions, respectively. Adjusting for the stresses measured in the as-received material, we have 185 and 18 MPa in the bend and transverse directions, respectively. Note that the adjustments are not correct unless the as-received stresses are from a sample that has no stress with depth gradient, which we know is not the case. However, the results do give us a qualitative feel that the system is accurately measuring the correct stresses within the limits of the analysis, and can do so with good repeatability.

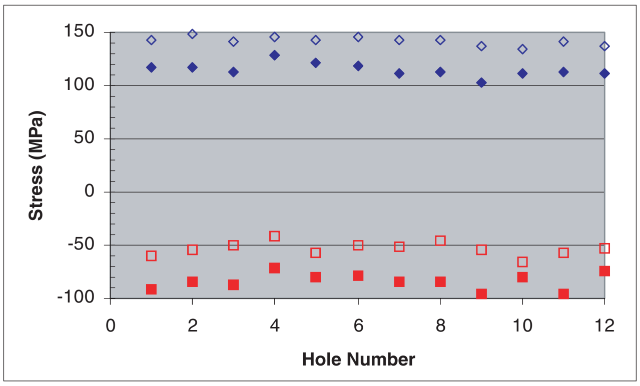

Fig. 8: Measured stress at depths of 0.3 and 0.5 mm depths (filled and open data points, respectively, with blue data in the bending direction, and red data in the transverse direction) with applied bending stress of 207 MPa

CONCLUSION

The residual stress measurements reported here show that good accuracy is possible with the ESPI hole drilling technique. In addition to good accuracy, the system has the benefits of a low incremental cost and rapid cycle time compared to traditional hole drilling methods. This will allow studies to be done where significant amounts of data need to be acquired, giving statistical basis to the results, and allowing residual stress studies to be done that might be prohibitively expensive with traditional methods.

The analysis technique described in this series is only strictly accurate for measurements where there is no stress with depth gradient, however, we have seen that there is

Depth (mm)	σ bend (MPa)	Std. Dev. (MPa)	σ trans (MPa)	Std. Dev. (MPa)
0.05	-50.8	17.0	38.6	20.1
0.1	-163.1	19.8	-187.7	17.7
0.3	-78.7	6.3	-111.6	2.8
0.5	-43.3	4.3	-71.3	5.7

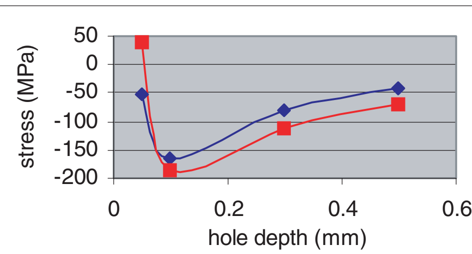

Fig. 7: Measured stress as a function of hole depth in as-received sample (blue data along intended bend axis, red data along transverse direction)

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good quantitative information in a sample with a gradient, by interpreting the results from multiple holes drilled at different depths in the same part.

In the near future, algorithms that analyze results from holes drilled in several increments will be available. We have started testing such an algorithm, and several other research groups are working toward the same thing. When fully tested and validated, this capability, coupled with the speed of ESPI hole drilling, could provide residual stress studies with significant economic savings compared to current RS measurement techniques.

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