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Residual Stress Measurement
By
The Hole Drilling Method

Hole drilling and x-ray diffraction are the most commonly used methods for residual stress measurement. The former method, while more labor intensive, is the most widely used because the required equipment are less expensive and portable; equipment portability makes hole drilling especially suitable for field applications. ASTM E 837 [(1)] is the accepted industry standard for residual stress measurement by the hole drilling method. A detailed explanation and interpretation of the ASTM and related background are presented in a Technical Note by the Measurements Group.[(2)]

According to the ASTM, a three-element strain gage rosette is affixed at each location where residual stress measurements are to be made; the elements are arranged around the circumference of a circle. A small hole, with a diameter D_0, is then drilled at the geometric center of the rosette. The strain gage circle diameter (D) of the commonly used rosettes can be 0.101, 0.202 and 0.404 in., respectively intended for use with holes with nominal D_0 of 1/32, 1/16 and 1/8 in; in this work, a 1/16 (0.0625) in. hole diameter is used. To provide flexibility, the ASTM allows variations in hole diameter, provided that $0.3 < D_o / D < 0.5$. Figure I shows the schematic arrangement of the strain gage elements, which are numbered 1, 2 and 3; these elements, respectively, measure strains ε_1, ε_2 and ε_3. One of the strain gage elements, number 1, is used in the ASTM as a reference for measuring the angles to be used in the computations; for simplicity, these angels are not shown or used here. For materials thicker than 4 D_o, as is the case for the blades, the drilled hole is blind and its depth is 0.4 D; for thinner gage materials, the hole may be through the thickness. The strain gage circle diameter (D) is marked on the rosette by the manufacturer and a depth indicator is used to monitor and record hole depth through out the drilling operation. A precision milling guide and a microscope are used to position the hole at the center of the rosette.

The strain gages measure the relieved strains (ε_1, ε_2, ε_3) at specified depth increments, as the hole is being drilled. The strains measured at the bottom of the hole are used to compute the maximum and minimum principal stresses, using equation 1, which is derived for a biaxial stress state.

$$\sigma_{min}, \sigma_{max} = \{(\varepsilon_3 + \varepsilon_1) / 4 A\} \pm \{[(\varepsilon_3 - \varepsilon_1)^2 + (\varepsilon_3 + \varepsilon_1 - 2 \varepsilon_2)^2]^{1/2} / 4 B\} \quad \text{........................ Equation 1}$$

Where A and B are calibration constants.

In through hole analysis, accurate values of the calibration constants, A and B, may be obtained by theoretical considerations, if desired. This is contrasted by blind hole analysis, where these coefficients must be determined by empirical means; that is, by experimental calibration or by numerical procedures such as finite element analysis. The ASTM utilizes the second approach and the A and B values are computed from equations 2 and 3, respectively.

$$A = - \{(1 + \mu)/ 2 E\} a \quad \text{.. Equation 2}$$

$$B = - (1/ 2 E) b \quad \text{.. Equation 3}$$

In equations 2 and 3, E is Young's modulus and μ is Poisson's ratio, whereas a and b are dimensionless, material independent coefficients. For aluminum alloys, E and μ are 10×10^6 psi and 0.33, respectively. Coefficients a and b, on the other hand, depend on the ratio D_0 / D. These coefficients were derived, by Schajer,[3] from finite element analysis and are listed in Table 2 of the ASTM for D_O / D ratios in the 0.3-0.5 range. It is important to know the exact value of D_0, so as to compute the appropriate values of the A and B constants from the a and b coefficients; the values of the a and b coefficients depend on the D_0 / D ratio. The exact value of D_0 may be determined in trial runs, prior to data collection, or at the conclusion of drilling. It is important to realize that the a and b values listed in Table 2 of the ASTM are

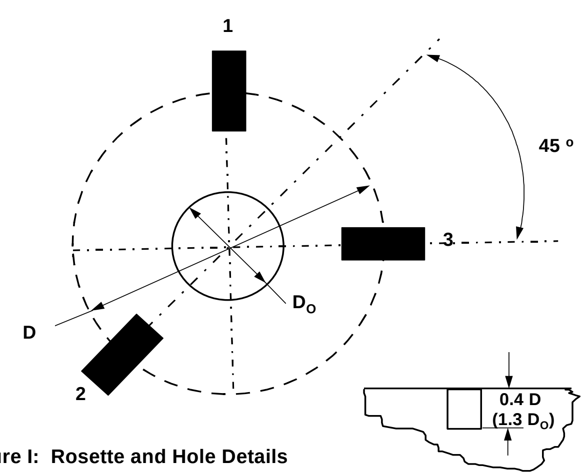

Figure I: Rosette and Hole Details

full depth coefficients that can be used only when the hole depth is about 0.4 D. Hole depth is monitored constantly by the depth indicator throughout the drilling operation.

In equation 1, the negative square root is associated with σ_{max} because the calibration constants, A and B, have negative numerical values. Furthermore, σ_{max} is the "most tensile" principle stress whereas σ_{min} is the "most compressive" one. It is important to note that "most tensile" could be compressive and that "most compressive" could be tensile. It is also important to note that a tensile (+) residual stress will produce a compressive (–) relieved strain, and vice versa.

Accept / reject criteria are based on the stresses computed at the bottom of the hole. The ASTM does not list any such criteria, and it is understood that these must be specified by the user. When specifying accept / reject criteria, the hole size to be used must also be specified. This is because computed stresses depend on hole depth, which, in turn, is a function of hole diameter D_O. In general, larger holes are preferred because of the increased sensitivity. Smaller holes, on the other hand, may be more suitable for tight spots, or where curved surfaces with small radii of curvature are involved.

The ASTM states that the computed stress values would be inaccurate if a nonuniform residual stress distribution exists. The procedure used to test for uniformity is to monitor certain strain functions ($\varepsilon_1 + \varepsilon_3$, $\varepsilon_3 - \varepsilon_1$ and $\varepsilon_1 + \varepsilon_3 - 2\,\varepsilon_2$) during the incremental drilling and plot them as functions of the Z (hole depth) / D ratio. These graphs should yield data points that are very close to, or coincident with, the curves depicted in Figure 4 of the ASTM. Data points which are removed from the curves by more than $\pm$ 3% indicate either substantial stress non-uniformity through the thickness, or strain measurement errors. In either case, the measured data are not acceptable for residual stress computations by the ASTM method. Even when the data points are close to the depicted curves, the ASTM points out that the graphical test thus described is not a sensitive indicator of stress uniformity. In other words, specimens with non-uniform stress fields can yield data points that are very close to the depicted curves. What is being said here is that there is no absolute test to verify the stress uniformity that is a prerequisite to using the ASTM method. Reference 2 presents additional information, not described in the ASTM, regarding stress uniformity. These are discussed in the Addendum.

The ASTM method is based on an assumption that the residual stresses are uniformly distributed through the depth and that the computed stresses are less than 50% of the yield strength of the material. It is highly unlikely that a uniform stress distribution will result from a surface rolling operation, especially in view of the small size of the roller with respect to that of the workpiece. In addition, the uniformity test, provided in the ASTM, does not guarantee that residual stress distribution is, indeed, uniform. Apart from this, the actual depth of the cold worked layer is not, in any way, related to the depth of the drilled hole. Furthermore, the computed stress, be that σ_{min} or σ_{max}, at the bottom of the hole (or at any other depth) does not represent the actual residual stresses at that location. Rather, it represents an equivalent uniform stress, from the surface to the bottom of the hole, which would produce the same relieved strain. The above limitations render questionable the effectiveness of hole drilling as a quantitative quality control tool to assess the effectiveness of the rolling operation.

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References

(1) ASTM E 837 - 95.
(2) Technical Note TN-503-5, Measurements Group, Inc., Raleigh, North Carolina. Phone: (919) 365-3800.
(3) Schajer, G.S., *Journal of Engineering Materials and Technology,* 110 (4), 1988; Part 1: p.p. 338-343; Part II: p.p. 344-349.

ADDENDUM

The Stress uniformity Issue

Further insight into the likely residual stress distribution can be gained by computing, at each depth increment, the equivalent uniform (EU) principle residual stresses, using the incremental strain release data obtained during drilling. [1]

The EU stress is that stress magnitude which, if uniformly distributed, would produce the same total relieved strain, by drilling from the surface to that depth. For these incremental stress computations, the full depth a and b coefficients cannot be used. Rather, the partial depth coefficients must be used. These have been determined by Schajer, [3] from finite element analysis, and are plotted against Z (hole depth) / D for different D_O / D ratios in Figure 11 of Reference 2; partial and full depth coefficients are also incorporated in hole drilling software such as "Restress," offered by the Measurements Group. The partial depth a and b coefficients are read directly from the graph and substituted in equations 2 and 3, to compute the corresponding A and B values which, in turn, are used to compute the equivalent uniform stress from equation 1. At the bottom of the hole, the full depth coefficients (Table 2 of the ASTM) are used.

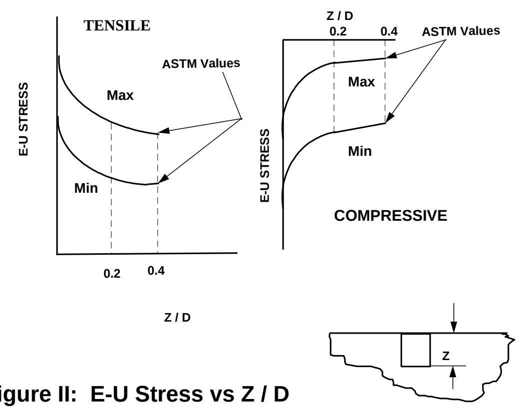

Figure II: E-U Stress vs Z / D

Figure II shows typical stress profile trends obtained from E-U stress computations, when a stress gradient is imposed on an initially stress free sample. [2] In general, when tensile residual stresses are introduced on the surface (e.g., by improper machining), they become less tensile with depth. Similarly, when compressive residual stresses exist on the surface (e.g., as a result of rolling), they become less compressive with depth. If, in error, the full depth a and b coefficients are used in the above computations, the reverse trends would result. Even when the partial depth coefficients are used, it is possible that the reverse trends could prevail for a short distance below the surface, eventually reverting to the typical trends at larger depths. It is noted that the above trends apply only when the stress gradient is imposed on a stress free material. In practice, however, stress gradients are introduced in materials that already have preexisting stress gradients. For example, a heat-treated aluminum alloy part will have a certain stress gradient, as a result of quenching during heat treatment. If, subsequent to heat treatment, the surface is rolled, new stress fields will be generated, and these will modify the preexisting stress gradient. In such cases, it would be unreasonable to expect that the trends thus described would be obtained. Figure II also shows that, as the hole depth Z approaches 0.40 D, the computed stress data become less dependent on depth; that is, as Z approaches 0.40 D, the computed stresses will not change significantly with depth. This is because the strain gages collect the strain release data at the surface, where the rosette is affixed. As the hole gets deeper, the strain gages become less sensitive to additional strain release taking place at the bottom of the hole. At full depth, the total strain is predominantly influenced by the layers closest to the surface. That is why about 80% of the total strain relief normally occurs in the first half of the hole. Thus, little, if any, quantitative interpretation can safely be made of the incremental strain data for increments beyond Z / D = 0.2. This is the case whether or not the stress gradient is introduced in a stress free material or on a preexisting gradient / stress field. Note that the stresses computed at the bottom of the hole will be those required by the ASTM.

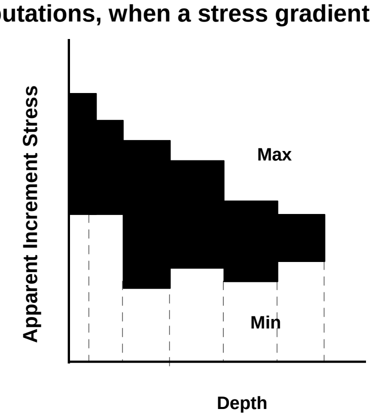

Figure III: Apparent Stress vs Depth (Tensile Case)

The incremental strain release data obtained can be examined in a different way by computing the ''apparent" E-U stress in each increment. This is done separately for σ_{min} and σ_{max} as follows:

$\grave{\sigma}_n = \{(\sigma_n Z_n) - (\sigma_{n-1} Z_{n-1})\} / Z_n Z_{n-1}$ .... Equation 4

Where: $\sigma`_n$ = "apparent" E-U stress in the n^{th} drilling increment

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[1] *In actual practice, the drilling tool is withdrawn after each increment had been drilled. In regions with tensile residual stresses, this would allow the drilled hole to "shrink," a process that would otherwise be prevented by the presence of the tool. When the hole is allowed to shrink, the strain gages will record more realistic strain release data.*

[2] *Had the stress been uniform, the data should plot as two straight horizontal lines (except for experimental scatter).*

σ_n, σ_{n-1} = E-U stress from the surface to depths Z_n and Z_{n-1}

Z_n, Z_{n-1} = depths of drilling increments n and n-1

The preceding calculation is performed individually for each principal stress at each depth increment. The computed stresses are based only on the strain release from the top to the bottom of a given drilling increment. Figure III shows an example of the resulting graphs.

Neither the E-U nor the "apparent" E-U represents actual residual stresses, except when the stresses are uniformly distributed. These computed stresses, however, can be very useful in identifying the presence of non-uniform stresses and in indicating stress distribution trends. Furthermore, in the first depth increment, both of the preceding methods of analysis will produce the same computed stresses. When that first increment is shallow enough and the measurements of strain and hole depth are reasonably accurate, the computed stresses should provide a good estimate of the average actual stress in the increment. The stresses computed for the second and subsequent depth increments are ever less subject to quantitative interpretation. This is because the change in strain produced through any subsequent increment is caused only by the residual stresses in that subsequent increment. The remainder of the incremental relived strain is generated by the residual stresses in the preceding increments, due to the increasing compliance of the material, and the changing stress distribution, as the hole is deepened. While the computed E-U and "apparent E-U stresses do not represent actual stresses, they can provide at least qualitative information about the stress variation with depth.