An Evaluation of Four Hole Drilling Analysis Techniques with respect to Non-Uniform Residual Stress Fields

INTRODUCTION

A wide variety of residual stress measurement techniques exist, but hole drilling is one of the most widely used. It is relatively simple, inexpensive, quick and versatile, and can be both laboratory-based and portable. However, achieving high quality, accurate stress data is not trivial. Meticulous measurement practice is crucial to obtaining good quality strain data, as is the choice of data analysis method. Applying the incorrect analysis technique may result in meaningless residual stress data.

Many workers continue to use inappropriate analysis techniques for measuring residual stress particularly where the stress field is non-uniform. Although a qualitative indication of the sign and magnitude of the residual stresses present may be obtained, accurate and depth-resolved values are only possible by applying the appropriate technique.

This Measurement Note examines four techniques for analysing residual strain data: the Uniform Stress, Equivalent Uniform Stress, Power Series and Integral methods. Results show that the Integral method is most applicable for non-uniform stress fields, in particular those where the stress varies rapidly with depth.

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BACKGROUND

The incremental hole drilling method is an accepted and widely used technique for measuring residual stresses. It is relatively simple, inexpensive, quick and versatile. A variety of laboratory-based and portable equipment is available (Figure 1), and the technique can be applied to a wide range of materials and components. The technique is often described as 'semi-destructive' as the volume of material removed is relatively small and can often be tolerated or adequately repaired.

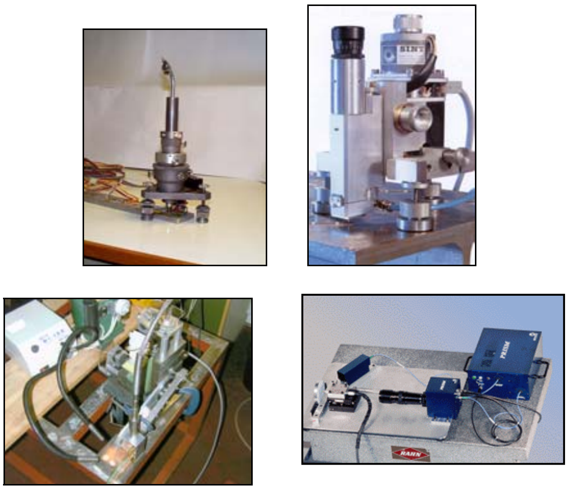

Figure 1 –Typical commercial hole drilling rigs (clockwise from top left: Vishay Measurements Group, HBM, HYTEC Inc., Stresscraft Ltd)

The hole drilling principle was first proposed by Mathar in 1934 [1] and since that time, many researchers have further developed the technique, resulting in a standardized procedure ASTM E837 [2].

The basic hole drilling procedure involves drilling a small hole into the surface of a component at the centre of a special strain gauge rosette (Figure 2) and measuring the relieved strains. The residual stresses originally present at the hole location are then calculated from these strain values. Incremental hole drilling, which involves carrying out the drilling in a series of small steps, improves the versatility of the method and enables stress profiles and gradients to be measured.

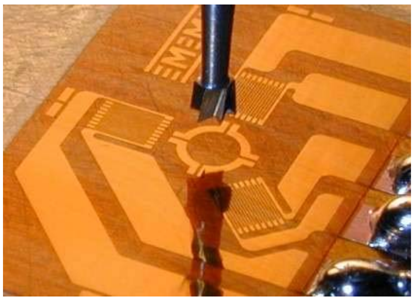

Figure 2 – Hole drilling into a special target strain gauge rosette (picture courtesy of Stresscraft)

The most common objective of hole drilling measurements is to evaluate in-plane residual stresses that can be assumed to be uniform with depth either from the surface of a thick specimen, or through the thickness of a thin specimen. ASTM E837 refers to these cases. However, in many practical cases, the residual stresses are not uniform with depth. For example, a shot-peened material has high compressive stresses close to the surface, with much smaller tensile stresses in the interior, and also weld residual stresses are highly non-uniform. In such cases, the assumption of uniform stress with depth may give a misleading solution.

A recent Round Robin exercise [3] demonstrated that many workers still routinely use inappropriate data analysis routines to calculate residual stresses in cases where the stress varies non-uniformly with depth. As a result of this exercise, a Measurement Good Practice Guide has recently been published [4] which provides both the inexperienced user and the expert with a practical guide to achieving better measurements. In this document, recommendations are presented related specifically to the implementation of appropriate data analysis techniques.

This Measurement Note compares four methods for calculating residual stresses from measured strain values. Commercial software has been used to analyse incremental residual strain data using three different methods [5]. These are the Uniform Stress, Power Series and Integral Method. A previous version of the software [6] analysed the data using the Uniform Stress and Equivalent Uniform Stress Method. Both pieces of software are used in this study.

ANALYSIS TECHNIQUES

The four methods to be compared are as follows (notation in parentheses used in following graphs):

Uniform Stress Method (U) – This is the method specified in ASTM E837. It assumes that the residual stresses are ***uniform*** with depth from the specimen surface. Thus, the method has no spatial resolution. However, when the measured residual stresses are truly uniform, this is the method of choice because it is the least sensitive to the effects of experimental error.

Equivalent Uniform Stress Method (EUS) – This method of data analysis is described in the Measurements Group Technical Note MG TN 503-5 [7]. The *Equivalent Uniform Stress* is defined as that stress magnitude, which, if uniformly distributed through the thickness would produce the same total relieved strain, at any depth, as measured during hole drilling. If the residual stress varies with depth, the stresses at incremental depths do not represent the actual residual stress, but the *equivalent uniform* stress that would produce the same relieved strain at that depth. The results from this technique can be difficult to interpret but can provide qualitative information about the stress variation with depth. Also known as the *average stress* method, it is useful only when experimental calibration is available.

Power Series Method (P) – This technique was first proposed by Schajer in 1981 [8] as an approximate method of calculating non-uniform stress fields from incremental strain data. It provides a limited amount of spatial resolution by assuming that the residual stresses vary ***linearly*** with depth from the specimen surface. Finite element calculations are used to relate the 'removed stresses' to the measured strains by computing a series of coefficients corresponding to the strain responses measured during hole drilling. The method is more sensitive to the effects of experimental errors but is a good choice when the measured residual stresses vary smoothly with depth.

Integral Method (I) – In the integral method, the contributions of the total measured strain relaxations of the stresses at all depths are considered simultaneously [9]. This provides a separate evaluation of residual stress within each increment of depth. Thus, the spatial resolution is the highest of all the calculation methods and is the method of choice when measuring rapidly varying residual stresses. However, the sensitivity of the calculated stresses to small experimental errors is also the most severe. The problem rapidly deteriorates if an attempt is made to increase spatial resolution by using many small hole depth increments. In practice, five or six increments yield a satisfactory level of detail for many stress distributions. If this number is significantly increased, residual stresses between successive calculation increments are seen to oscillate about the true stress level. Any additional 'smoothing' of the strain data to reduce oscillation and permit the use of smaller stress calculation increments is unlikely to reveal a significant increase in the detail of the 'true' stress distribution.

Figure 3 shows a comparison of the results of four stress calculation methods for a non-uniform stress field [9]. The integral method gives a good stepped approximation to the actual stress variation with depth, and the power series method gives a close straight-line fit. The other methods give much less satisfactory results because they are essentially 'calibrated' using uniform stress field data.

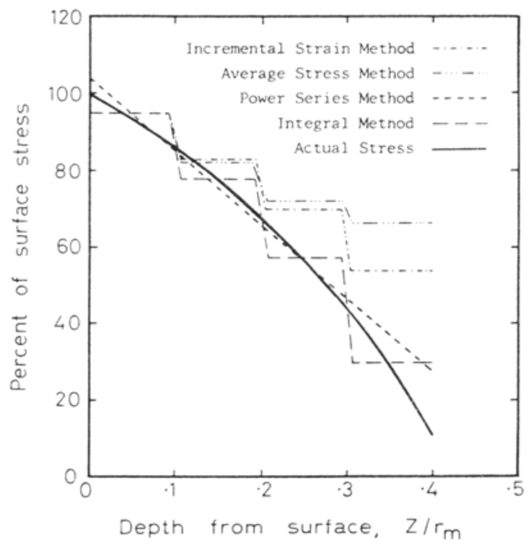

Figure 3 – Comparisons of the results from four stress calculation methods [9]

TEST FOR NON-UNIFORMITY

In general, the nature of the residual stresses is not known in advance of the measurement. Good engineering judgement combined with a knowledge of the stresses expected should be used to choose the most appropriate calculation method.

ASTM E 837 states that a test should be made to check that the residual stresses are uniform within the hole depth. This is extremely important, as the analysis becomes invalid for significantly non-uniform stress fields. The Standard outlines the graphical procedure for determining stress uniformity based on combination strains.

The following combination strains are initially calculated:

$$p = \frac{(\varepsilon_3 + \varepsilon_1)}{2} \qquad \{1\}$$

$$q = \frac{(\varepsilon_3 - \varepsilon_1)}{2} \qquad \{2\}$$

$$t = \frac{(\varepsilon_3 + \varepsilon_1 - 2\varepsilon_2)}{2} \qquad \{3\}$$

where ε_1, ε_2, and ε_3 refer to the individual strain gauge readings at each hole depth.

Next, the numerically larger set of combination strains q or t is determined. Each set of combination strains p and the larger of q and t are then expressed as a percentage of their values when the hole depth = 0.4D (D = diameter of the gauge circle). These percentage strains are plotted against normalized hole depth (hole depth/D). Data points that deviate by more than ±3% from the curves presented in the standard indicate either substantial stress non-uniformity through the material thickness, or strain measurement errors. In either case, this indicates that analysing the data assuming a uniform stress distribution through the thickness will yield false results.

Figure 4 plots the normalised strain data in this way. The data points indicate the percentage values of the specified strains and the curves show the limits of the two largest computed combination strains (equations {1}-{3}). The example in Figure 4 shows a good comparison between the data points and the theoretical curves, validating the assumption of a uniform stress field.

This approach may be extended further by calculating the strain values for the theoretical case where the residual stresses are uniform with depth. These are compared with the measured data and any significant deviation once again indicates significant stress non-uniformity. In Figure 5 (same data as Figure 4) the dashed and solid lines closely coincide confirming stress uniformity with depth.

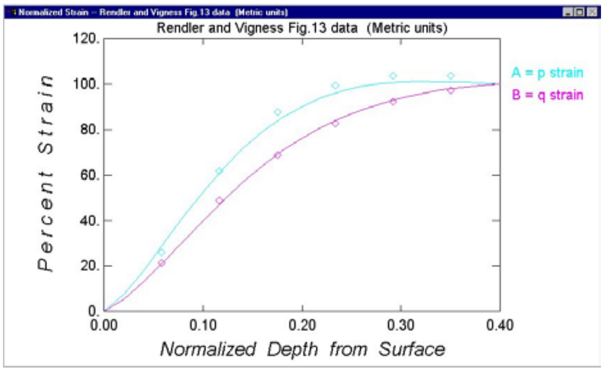

Figure 4 – Typical "Normalised Data" window

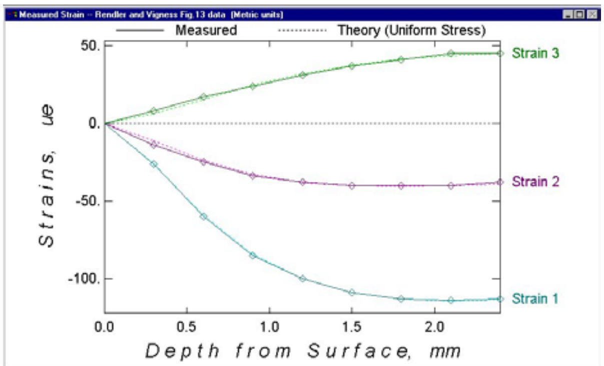

Figure 5 – Typical "Measured Strain" window

UNIFORM STRESS FIELDS

Figures 4 and 5 use the strain data measured by Rendler and Vigness [10], presented in Table 1.

The strain data was measured on a cold-rolled steel specimen with a hole diameter of 1.59mm. The test specimen had been subjected to an applied tensile stress that was uniform throughout the cross-sectional area of the sample.

It is clear from Figures 4 and 5 that the stress field satisfies the validity criteria, and so the use of the Uniform Stress Method is appropriate for this case. The maximum and minimum principal stresses can be calculated to be 105MPa and -5MPa respectively through the thickness. Stresses close to the surface have a much greater influence than those at greater depths. Thus, the displayed values mostly describe the stresses close to the surface, with only minor contributions from the interior stresses. Beyond a certain depth (typically equivalent to the hole diameter) the stresses have almost no effect on the relieved surface strains and can be ignored.

Hole Depth (mm)	$\mu\varepsilon_1$	$\mu\varepsilon_2$	$\mu\varepsilon_3$
0	0	0	0
0.3	-26	-14	8
0.599	-60	-25	17
0.899	-85	-34	24
1.199	-100	-38	31
1.499	-109	-40	37
1.798	-113	-40	41
2.098	-114	-40	45
2.398	-113	-38	45

Table 1 – Strain data as measured by Rendler and Vigness [10]

NON-UNIFORM STRESS FIELDS

The aforementioned round robin exercise [3] examined the stress profile in a shot-peened spring steel. Shot-peening is a cold working process in which the material is bombarded with small spherical metal balls called shot (Figure 6). Each shot imparts a small indentation or dimple to the surface of the material, which overlap and develop a uniform layer of residual compressive stress at the surface. It is well known that cracks will not generally initiate or propagate in a compressively stressed zone and since nearly all fatigue and stress corrosion failures originate at the surface of a part, compressive stresses induced by shot-peening provide considerable increases in component life. The maximum compressive residual stress produced close to the surface of a shot-peened part can be at least one half the yield strength of the material itself. Many materials will also increase in surface hardness due to the cold working effect of shot-peening. This example is therefore an ideal case to consider the analysis of non-uniform stress fields, as the expected profile is a high compressive stress field in the surface balanced out by lower tensile stresses through the thickness of the material.

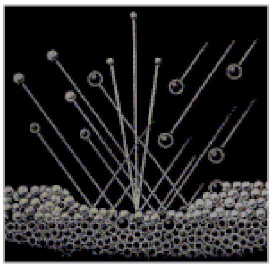

Figure 6 – Shot-peening process

The data to be examined was obtained by one of the Round Robin participants and was typical of the data generated. In this case, a UM-type strain gauge rosette (Figure 7) with a gauge circle diameter of 5.131mm was used. A hole diameter of 2.12mm was measured following testing. For the purpose of all subsequent calculations, the material was assumed to have a Young's modulus of 210 GPa and a Poisson's ratio of 0.3.

Table 2 shows the measured relieved strains obtained via incremental hole drilling down to a depth of 2 mm.

Hole Depth (mm)	$\mu\varepsilon_1$	$\mu\varepsilon_2$	$\mu\varepsilon_3$
0.1	100	113	110
0.2	215	239	238
0.3	297	332	332
0.4	337	380	388
0.5	363	409	416
0.6	380	430	440
0.7	392	444	459
0.8	399	454	465
0.9	407	462	476
1.0	410	468	481
1.1	413	472	485
1.2	416	474	488
1.4	418	478	492
1.6	420	481	494
1.8	421	483	497
2.0	421	484	499

Table 2 – Incremental hole drilling strain data from a shot-peened spring steel [3]

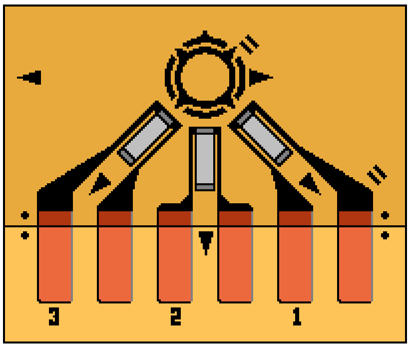

Figure 7 – A UM-type strain gauge

Figures 8 and 9 present the measured and normalised strain data windows respectively from the analysis [5]. It is clear that in this case, the theoretical and measured values do not coincide and therefore the assumption of a uniform stress field is invalid.

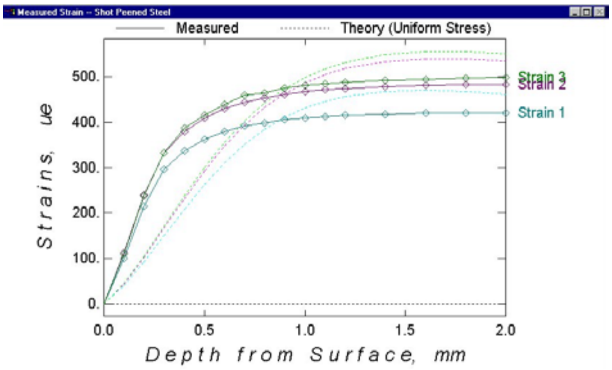

Figure 8 – Measured strain data vs. depth including theoretical strain values for a uniform stress field

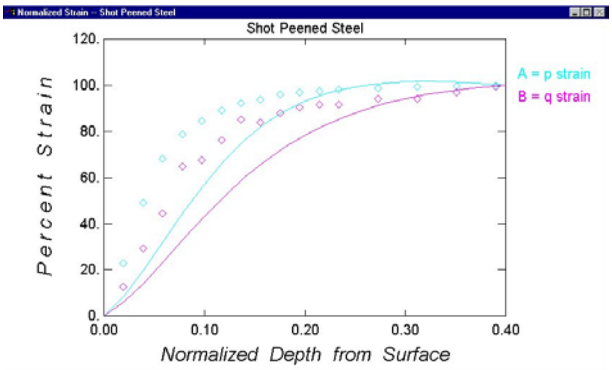

Figure 9 – Normalised (with depth) strain data for largest combination strain values

Although it has been shown that the assumption of a uniform stress field is incorrect, it is useful to examine the effect of analysing the data via the four techniques described previously. Figure 10 plots the residual stress values for these four cases.

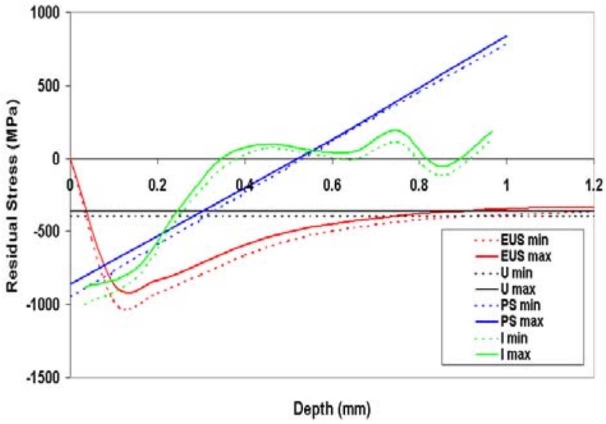

Figure 10 – Residual stress plot for a non-uniform stress field comparing various analysis techniques

All four methods produce significantly different curves.

It is well-known that shot-peening produces a highly compressive stress close to the surface of the material which is balanced by tensile forces into the depth. Clearly, this expected stress profile is only obtained via the integral method. The main conclusions from this figure are that

- The uniform stress approach is clearly not suitable.

- The equivalent uniform stress method does not predict a compressive stress at the surface of the material and it is only at about 0.1mm that the magnitude of the stress equals that of the integral plot. As the depth increases, the stresses become less compressive but never reach zero or tension. (Note that the stress level predicted by both the equivalent uniform stress method and the uniform stress method plateau at the same value (~ -350MPa at ~ 1mm)). Therefore, in the presence of significant stress gradients, the difference between the equivalent uniform stress and the actual stress increases with each depth increment.

- The power series method indicates a compressive stress near the surface of the material, but predicts a linear stress field through the thickness. This means that at 1mm depth, a value of ~800MPa is predicted. However, although extremely simplified, it does follow the trend of the integral plot.

- Only the integral method has the necessary accuracy to resolve the sign and magnitude of the principal stresses through the thickness of the material. The stresses are calculated to become tensile at about 0.35mm, which agrees well with the expected stress profile and with measurements made with other techniques [3]. The stress oscillations after this point are a feature of the sensitivity of the technique to experimental error – i.e. small changes in strain at increased depths have a more significant effect on the calculated stresses.

So why does each technique generate such variations in data? During the hole drilling process, removal of material from the first drilling increment results in surface strains (at the gauge) that relate directly to the residual stresses relieved at the hole boundary within that increment. Removal of material from the second increment produces two effects. Firstly, the stiffness of the structure is changed such that there is further relief of stresses within the layer of material corresponding to the first increment, producing a strain change at the gauge. Secondly, stresses relieved at the hole boundary of the second increment produce an additional strain change at the gauge. Thus, even if the second increment contains no residual stress, any stress within the first increment will produce a change in strain at the gauge as the second increment is drilled.

Accordingly, different sets of coefficients are required to relate surface strain changes to residual stresses for each of the stress depth and hole depth combinations. Only the integral method takes into account these changes, using a different set of coefficients for each increment to achieve accurate measurement of non-uniform residual stress profiles.

Figure 11 presents three sets of shot-peened steel strain data from the NPL round robin study [3], originally analysed via the EUS method and subsequently re-analysed using the Integral method (each pair of identically coloured plots represent σ_{min} and σ_{max} for each set of incremental strains). The technique discrepancies are clear and only the Integral reanalysis obtains the expected profiles.

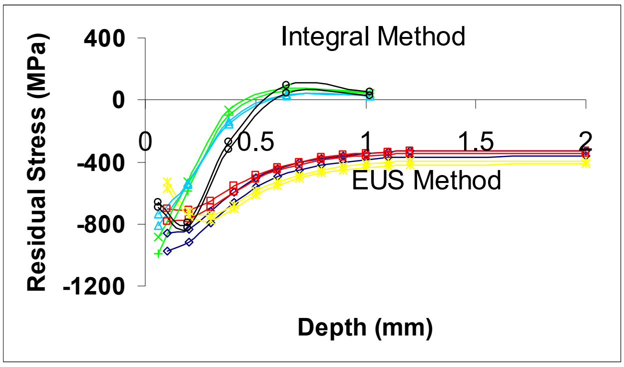

Figure 11 – Shot-peened steel residual stress data analysed via EUS and Integral methods

CONCLUSIONS

In order to obtain accurate residual stress measurements for hole drilling, it is imperative that an assessment is initially made of the nature of the stress field and secondly, the appropriate analysis technique applied. Users who continue to use the equivalent uniform stress method will obtain inaccurate residual stress measurements when examining non-uniform stress fields.

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ADDITIONAL INFORMATION

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