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**A NATIONAL MEASUREMENT
GOOD PRACTICE GUIDE**

No. 53

The Measurement of
Residual Stresses by the
Incremental Hole Drilling
Technique - Issue 2



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Measurement Good Practice Guide No. 53

- Issue 2

The Measurement of Residual Stresses by the Incremental Hole Drilling Technique

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Abstract:

Residual stresses can be defined as those stresses that remain in a body after manufacturing or processing in the absence of external forces or thermal gradients. Virtually all manufacturing and fabricating processes introduce residual stresses into the manufactured article and extreme service loading may also change the state of residual stress in the component. The effects of residual stress may be either beneficial or detrimental, depending upon the sign, magnitude and distribution of the stress. For improved process and product control, design, performance and modelling it is increasingly important to have rigorous experimental procedures to determine the residual stresses to the best possible accuracy.

A wide variety of residual stress measurement techniques exist, but centre 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. This guide provides both the inexperienced user and the expert with a practical guide to achieving better measurements. It draws together some of the background to the technique, discusses the current standards and highlights a number of key issues crucial to obtaining a good measurement, based on input from UK experts and some of the findings from recent UK hole drilling residual stress intercomparison exercises. The currently available residual stress data analysis techniques are discussed, and a comprehensive bibliography of key references is included together with some information and links to UK hole drilling contacts and to relevant web sites, providing the user with a valuable resource for further reading.

This new issue provides further advice and guidance on using the Integral method for analysing hole drilling data, and focuses in more detail on aspects of the technique relevant to fine-increment drilling, where the depth increments close to the surface may be of the order of 10-30µm, and which has been used for measuring near surface residual stress profiles and stresses introduced during machining and surface treatment. Some comment and guidance on recent developments and applications of non-contact strain measurement techniques in place of the conventional strain gauge rosette are also provided.

Where appropriate, examples are given to illustrate aspects of the measurements and issues covered.

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The Measurement of Residual Stresses via the Incremental Hole Drilling Technique

Contents

1	Scope	1
2	Symbols and Definitions	2
3	Introduction.....	3
3.1	Historical development of the hole drilling technique.....	4
3.2	Basic test procedure	5
3.3	Basic calculations	8
4	Current standard procedures and documentation	12
4.1	Overview of ASTM E837-01e1	15
4.2	Overview of Measurements Group TN-503-5	16
5	Practical issues associated with the measurements	18
5.1	Planning the measurements.....	18
5.2	Strain gauge selection	19
5.3	Surface preparation and installation.....	21
5.4	Strain gauge instrumentation	23
5.5	Alignment	24
5.6	Drill and hole size	25
5.7	Hole spacing	26
5.8	Zero depth detection	26
5.9	Selection of drilling increments	28
5.10	Drilling.....	29
5.11	Strain measurements	32
5.12	Measuring the hole dimensions	33
6	The Integral Method.....	34
6.1	Basic Approach.....	34
6.2	Practical Considerations.....	35
6.3	Examples and Issues	36
	<i>Example 1: Selection of depth increment and numbers.....</i>	<i>37</i>
	<i>Example 2: Abrupt change in stress</i>	<i>39</i>
	<i>Example 3: Effect of material non-linearity</i>	<i>41</i>
	<i>Example 4: Comparison of different analysis approaches</i>	<i>42</i>
	<i>Example 5: Conventional vs fine increment drilling</i>	<i>44</i>
	<i>Example 6: Effect of strain smoothing.....</i>	<i>46</i>
6.4	Conclusion	47
7	Non-contact strain measurement methods	49
8	Uncertainty analysis	51
9	Reporting of results	54
10	Summary of observations and recommendations.....	55
	Acknowledgements	58

References.....	58
Appendix 1 – Directory of UK Hole Drilling Experts and Contacts.....	63

1 Scope

This Measurement Good Practice Guide deals with the recommended procedure for measuring residual stresses using the **incremental centre hole drilling technique**. It is aimed primarily at measurements in metallic materials using conventional residual stress strain gauge rosettes, although this updated issue now contains a section on non-contact optical strain measurement. Some consideration is given to portable measurements in the field throughout the Guide, but it is primarily directed at laboratory measurements. Attention will be drawn to some of the key practical issues that will allow users to identify and reduce discrepancies in the results to obtain accurate and more consistent data.

In particular, the Guide:

- Reviews the current standards and documentation available for using the incremental hole drilling technique for determining residual stresses.
- Highlights and summarises some of the key **practical issues** in measuring residual stresses with this method that are not covered in the standard documentation, and provides guidelines for achieving reliable and accurate measurements.
- Presents **recommendations** on the most appropriate **data reduction and analysis** techniques for calculating residual stress values from measured strain data.
- Includes examples to illustrate aspects of the measurements and issues covered.
- Includes a comprehensive list of references, together with links to UK experts, hole drilling practitioners and relevant websites.

This new issue provides further advice and guidance on using the Integral method for analysing hole drilling data, and focuses in more detail on aspects of the technique relevant to **fine-increment drilling**, where the depth increments close to the surface may be of the order of 10-30µm, and which has been used for measuring near surface residual stress profiles and stresses introduced during machining and surface treatment.

Some comment and guidance on recent developments and applications of **non-contact strain measurement techniques** in place of the conventional strain gauge rosette are also provided.

2 Symbols and Definitions

Symbol	Definition	Units
ε_r	Relieved strain measured by the strain gauge	$\mu\varepsilon$
$\bar{A}, \bar{B}$	Calibration constants	
$\sigma_{\max}, \sigma_{\min}$	Maximum and minimum principal stresses	MPa
β	Angle measured clockwise from ε_r to $\sigma_{\max}$ direction	$^\circ$
$\bar{a}, \bar{b}$	Dimensionless hole drilling calibration constants	
ν	Poisson's ratio	
E	Young's Modulus	GPa
D	Gauge circle diameter	mm
D_o	Diameter of the drilled hole	mm
z	Depth of drilling	mm
$\varepsilon_{1,2,3}$	Measured relieved strains	$\mu\varepsilon$
p	Mean hydrostatic strain (combination strain)	$\mu\varepsilon$
q	Tensor shear strain 45° from x-y direction (combination strain)	$\mu\varepsilon$
t	Tensor shear strain in x-y direction (combination strain)	$\mu\varepsilon$
P	Combination stress corresponding to strain p	MPa
Q	Combination stress corresponding to strain q	MPa
T	Combination stress corresponding to strain t	MPa
R_a	Surface roughness	μm

3 Introduction

Residual stresses can be defined as those stresses that remain in a body after manufacturing or processing in the absence of external forces or thermal gradients. Virtually all manufacturing and fabricating processes introduce residual stresses into the manufactured article and extreme service loading may also change the state of residual stress in the component. The effects of residual stress may be either beneficial or detrimental, depending upon the sign, magnitude and distribution of the stress, all of which can be critical to performance and have to be considered in the design of a component.

The hole drilling method is an accepted and much examined technique and therefore this guide is not intended to provide a step-by-step guide to the procedure - new users should refer to ASTM standard E837-01e1 [1] and Measurements Group Technical Note TN-503 [2] for procedural information. However, an outline of the basic experimental procedure is included in Section 3.2 to allow new readers to familiarise themselves with the technique. Readers will also find a list of key references towards the end of the guide.

Centre hole drilling is one of the most widely used techniques for measuring residual stress [3]. It is relatively simple, inexpensive, quick and versatile; a variety of laboratory-based or portable equipment is available, 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. Limitations of the technique include the relatively poor strain sensitivity and the potentially large errors and uncertainties that may be present due to inaccuracies in introducing the hole (alignment, diameter, concentricity, profile, depth etc.), surface roughness, flatness, and specimen preparation. Incremental centre 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, providing appropriate analysis techniques are followed.

Although ASTM standard E837 and the Measurements Group Technical Note TN 503-5 have been in publication for some time, some of the practical issues and limitations have not been addressed in great detail. This Measurement Good Practice Guide therefore aims to review the scope of the two publications, and provide additional recommendations and advice for obtaining reliable and accurate residual stress data from incremental hole drilling. Key points and recommendations are highlighted in bold throughout the text and are summarised in Section 10.

It is interesting to note that some practitioners still consider the hole drilling technique to be mainly qualitative merely giving the sign and relative magnitude of the stresses present, an opinion that has probably come about through poor measurement practice. Many results are now available showing that excellent quantitative data can be achieved with meticulous experimental practice, appropriate data analysis, and an appreciation of the factors that contribute to the uncertainties in the measurement.

3.1 Historical development of the hole drilling technique

The principle of the hole drilling method is relatively straightforward. A small hole is drilled into the component, and the relieved surface strains caused by the introduction of the hole are measured using a specially designed strain gauge rosette. It is then possible to calculate the residual stresses that were originally present in the material, at the location of the hole, from the relieved strains via a series of calculations.

Mathar [4] first proposed the concept of using the hole drilling method for the determination of residual stresses in 1934, using a mechanical extensometer to measure the displacements around a circular hole drilled through a stressed plate. In 1950, Soete and Vancrombrugge [5] improved the measurement accuracy by using strain gauges instead of a mechanical extensometer, although at this point, the centre hole gauge that is commonplace today was not available. The first studies on developing the analysis technique focused on through thickness measurements on thin sheets or plate, where the residual stress was assumed to be uniformly distributed through the thickness. The solution for thick components was derived later from experimental and empirical measurements. Kelsey carried out the first investigation into the variation of residual stress with depth using the hole drilling method in 1956 [6].

Rendler and Vigness developed the hole drilling method further in 1966 [7] into a systematic and reproducible procedure, and the modern application of the hole drilling method for uniform stress fields dates from this work. They were also the first to define the geometry of the ASTM E837 standard hole drilling rosette. Since then, a number of workers have extended the technique, particularly the experimental practices and through development of more accurate and comprehensive data analysis routines. In 1974, Procter and Beaney were the first to use the air abrasion technique for stress-free hole drilling [8], and the use of an air turbine for ultra-high speed drilling (up to ~ 400,000 rpm) was first introduced by Flaman in 1982 [9].

More recently, focus has fallen on measuring the variation of residual stress with depth via incremental hole drilling and developing solutions for non-uniform stress fields. Modern computing and finite element techniques have allowed the development of residual stress calculation procedures that were not previously possible. In 1981 Schajer developed the first generalised finite element solution of the incremental technique, including tabulations of the calibration coefficients [10]. Bijak-Zochowski was the first to propose a method for calculating non-uniform stress distributions in 1978 [11] and Schajer again developed the appropriate calibration coefficients in 1988 [12].

Attempts have also been made to increase the accuracy and versatility of the technique, by the introduction of six-gauge rosettes for increased strain sensitivity, and taper hole drilling with some success [13]. Full field measurements have also been made using moiré interferometry, laser speckle interferometry, holography, and strain mapping in place of the conventional strain gauge rosette, and these are introduced in Section 7.

Although the literature surrounding the hole drilling technique is extensive there are still many practical issues that need to be considered. Some of these will be addressed in subsequent sections of the Guide.

3.2 Basic test procedure

The basic hole drilling procedure involves introducing a small hole into the surface of a component, at the centre of a special strain gauge rosette and measuring the relieved strains. The residual stresses originally present at the hole location are then calculated from these strain values. The measurement involves the following steps:

1. Installation of a special residual stress strain gauge rosette and instrumentation (for tips and information see Sections 5.2 to 5.4 of this Guide)
2. Alignment and setting up of the drilling fixture (see Sections 5.5 and 5.6)
3. Establishing the zero depth starting position (important for incremental drilling, less so for a single full depth measurement) (see Section 5.8)
4. Drilling, either to a single hole depth approximately equal to half the hole diameter or in a series of depth increments to obtain some indication of the variation of stresses with depth. (see Section 5.9 and 5.10)
5. Recording of the separate strain gauge readings at each depth increment
6. Calculation of the initial residual stress state from suitable data reduction calculations (see Section 6)

It should be noted that the basic technique described in ASTM E837-01e1 and Measurements Group TN-503-5 assume that the residual stress is uniform throughout the thickness of the specimen. If this is not the case (and in many practical situations it is not) other data analysis techniques should be used (see Section 6).

In the hole drilling procedure, a special 3-element residual stress strain gauge rosette is bonded to the surface of the component under consideration. Typical designs are shown in Figure 1 overleaf. The strain gauges are then connected to a suitable strain indicator and the alignment and zero depth positions set before drilling the hole. The hole is then drilled into the component to a depth approximately equal to half its diameter. (The actual size of the hole depends on the size of the strain gauge used). There are practical limitations on how deep the hole can be drilled and it is generally accepted that the maximum depth of hole used is approximately equal to half its diameter. There is little advantage by going deeper because the surface strain gauges are not sensitive to contributions at subsequent depth increments.

A selection of commercially available hole drilling rigs, which are shown in Figure 2, have been specially designed for this purpose. The various designs allow accurate positioning and alignment of the drill and most permit controlled incremental depth drilling.

Different techniques can be used to produce the hole including conventional drilling, abrasive jet machining and high speed air turbines, the relative merits of which will be discussed in more detail in Section 5.10.

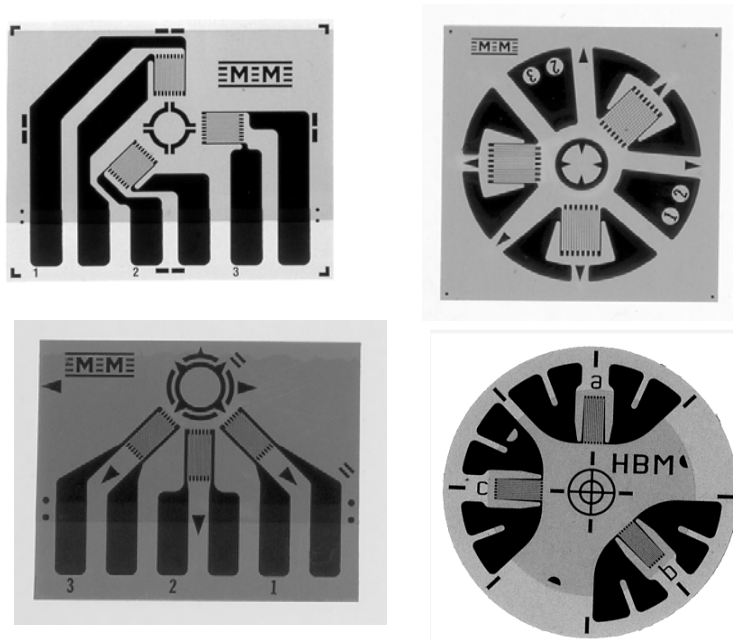


Figure 1: Typical hole drilling strain gauge rosette types

From the relieved strain values the next step is to calculate the original stress state in the component, using a series of equations given in Section 3.3. If drilling is carried out in a single step to the full depth it is only possible to obtain limited residual stress information and a single reading of the relaxed strains that represents the average residual stress present, but the generation of a profile of the variation of stress with depth is possible via incremental drilling.

ASTM E837 recommends that it is always preferable to drill the hole in small increments of depth, recording the observed strains and measured hole depth at each increment. Even if subsequent analysis is only used for the full depth case, this is necessary for judging whether the residual stresses are essentially uniform with depth, validating the use of the standard full-depth coefficients. If incremental measurements are not taken, there is no means for making references about stress uniformity and the calculated stresses may show considerable error.

The basic hole drilling calculations described in ASTM E837 and Measurements Group Technical Note TN-503 presented in Section 3.3 are strictly only valid when the residual stress field is uniform and does not vary significantly with depth. In such cases, the experimentally derived strain calibration coefficients developed from test specimens with known uniform stress fields can be used directly [7,14]. Strictly, these should not be used when the residual stress profile is non-uniform, where an *Average Strain Method* (often known as the **Equivalent Uniform Stress** or **EUS Method**), an *Incremental Strain Method* or *Power Series Method* is sometimes used.



Figure 2: Typical commercial hole drilling rigs (clockwise from top left: Measurements Group, HBM, HYTEC Inc., Stresscraft Ltd)

The *Equivalent Uniform Stress* (EUS) can be defined as the assumed uniform stress within the total hole depth that produces the same total strain relaxations as the actual non-uniform stress distribution. It is calculated using the strain relaxations measured before and after each hole depth increment. It is then assumed that the EUS after a hole depth increment equals the spatial average of the EUS before the hole depth increment plus the stress within the increment. **The EUS is useful for comparison purposes, but has limited value for practical engineering applications as the EUS value does not give a true value for the residual stresses present.**

The *Incremental Strain Method* was introduced by Soete and Vancrombrugge [5] in 1950 and further developed by Kelsey in 1956 [6]. With this approach the hole is drilled in a series of

increments and the strain relaxations measured after each depth increment. The stresses that originally existed within each hole depth increment are then calculated by assuming that the incremental strain relaxations are wholly due to the stresses that existed within that depth increment. For each depth increment, different values of calibration constants must be used.

The *Power Series* is another method that was proposed by Schajer [12] and assumes that the residual stresses vary linearly with depth. It is a reasonable choice if the residual stresses vary smoothly with depth but can lead to a misrepresentation of the stress profile if this is not the case, and generally has only limited applicability.

All of the analysis methods mentioned above have significant shortcomings. In particular, the assumption that the *EUS* equals the average stress over the hole depth is only true if the stresses at all depths within a given hole depth contribute equally to the strain relaxations measured at the surface. In practice, the stresses in the component closer to the surface contribute much more to the surface strain relaxations than do the stresses further from the surface. **Neither the *Equivalent Uniform Stress* nor the *Incremental Strain Methods* produce reliable results when there are significant variations of stresses with depth, and this is confirmed in both ASTM E837 and TN-503-5 documents. The *Power Series* approach gives a reasonable approximation if the stresses vary smoothly with depth, but generally has limited application.**

Finite element solutions of calibration data have opened new possibilities for improving the calculation of non-uniform residual stresses from incremental strain data via the *Integral Method*. In this technique, the contributions to the total measured strain relaxation of the stresses at all depths are considered simultaneously. The *Integral Method* will be examined in greater detail in Section 6, where it will be shown to be the preferred technique for accurate determination of residual stresses irrespective of the original stress distribution present in the component.

3.3 Basic calculations

ASTM E837 [1] covers the procedure for measuring the residual stresses in isotropic linear elastic materials, where the stresses do not vary significantly with depth. For this condition, the following basic calculations are used.

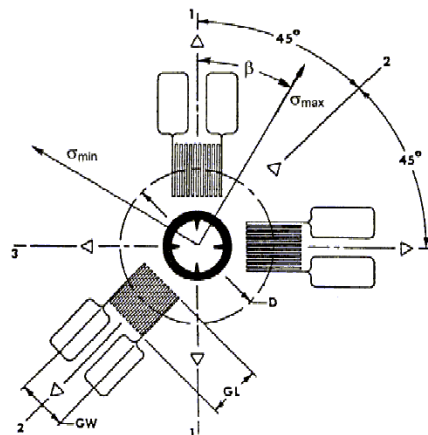


Figure 3: Schematic diagram showing the geometry of a typical three-element strain gauge rosette [1]

Figure 3 shows the geometry of the strain gauge rosette, and the preferred notation for the direction of the principal stresses [1]. In this design the three radially oriented gauges are arranged with their centres at a distance $D/2$ from the gauge target and the centre of the hole. Although, in theory, the angles between the gauges can be chosen arbitrarily, the simplest analytical calculations are achieved with 45° , and this is now the standard for most commercially available designs. In the figure above, which shows the ASTM Type A rosette design, gauge 2 has been transposed to be diametrically opposite its original position to give more sampling about the hole position and a larger grid size. The ASTM Type B designs have all 3 gauges on one side of the hole to allow the gauge to be used more closely to obstructions such as corners, fillet radii or welds.

The surface strain relief is related to the relieved principal stresses by the following relationship:

$$\varepsilon_r = (\bar{A} + \bar{B} \cos 2\beta) \sigma_{\max} + (\bar{A} - \bar{B} \cos 2\beta) \sigma_{\min} \quad \{1\}$$

The two calibration constants $\bar{A}$ and $\bar{B}$ depend on the geometry of the strain gauge used, the elastic properties of the material and the radius and depth of the hole. Because the gauges themselves have a physical size and measure an average strain rather than a point value, coefficients $\bar{A}$ and $\bar{B}$ are obtained by integrating over the active gauge area. For a given set of material properties $\bar{A}$ and $\bar{B}$ are constant if the geometry of the strain gauge rosette remains the same, and thus apply to all sizes of rosette of a particular geometry.

For a material with given elastic properties, the following equations can be used to evaluate the constants $\bar{A}$ and $\bar{B}$:

$$\bar{A} = \frac{-\bar{a}(1+\nu)}{2E} \quad \{2\}$$

$$\bar{B} = \frac{-\bar{b}}{2E} \quad \{3\}$$

where $\bar{a}$ and $\bar{b}$ are dimensionless, almost material-independent constants that vary with the hole depth. They represent the strains measured for unit cases of ‘pressure’ ($\sigma_{\max} = \sigma_{\min} \neq 0$) and ‘shear’ ($\sigma_{\max} = -\sigma_{\min}$) stresses, respectively. The coefficients can be determined by experimental calibration but the values for Measurements Group Types A, B and C gauges are tabulated in the ASTM E387 standard, based on numerical analyses and finite element studies over the practical limits of hole diameters and depths.

For a **thin** specimen or a through thickness hole (plane stress conditions), the strain relaxations measured by the three strain gauges should be considered and the following **combination strain** variables calculated:

$$p = \frac{\varepsilon_3 + \varepsilon_1}{2} \quad \{4\}$$

$$q = \frac{\varepsilon_3 - \varepsilon_1}{2} \quad \{5\}$$

$$t = \frac{\varepsilon_3 + \varepsilon_1 - 2\varepsilon_2}{2} \quad \{6\}$$

where p represents the 'volumetric' strain relaxation, and q and t represent the shear strain components.

It is not necessary at this stage to consider the corresponding combination stress variables as no incremental strain relief is being performed. The angle β may be computed via the following equation:

$$\beta = \frac{1}{2} \arctan(t/q) \quad \{7\}$$

where β is the angle measured clockwise from gauge element 1 to the direction of the maximum or minimum principal stress, thus :

$$\begin{aligned} \text{If } \varepsilon_3 > \varepsilon_1 & \text{ then } \beta \text{ refers to } \sigma_{\max} \\ \text{If } \varepsilon_1 < \varepsilon_3 & \text{ then } \beta \text{ refers to } \sigma_{\min} \\ \text{If } \varepsilon_1 = \varepsilon_3 & \text{ then } \beta = \pm 45^\circ \end{aligned}$$

The principal stresses are then calculated from the following equation:

$$\sigma_{\min}, \sigma_{\max} = - \left[\left(\frac{p}{a(1+\nu)} \right) \pm \left(\frac{\sqrt{(q^2 + t^2)}}{b} \right) \right] E \quad \{8\}$$

For a **thick** specimen ($>1.2D$, where plane strain conditions exist) the **combination stresses** should be considered:

$$P = \frac{(\sigma_3 + \sigma_1)}{2} \quad \{9\}$$

$$Q = \frac{(\sigma_3 - \sigma_1)}{2} \quad \{10\}$$

$$T = \frac{\tau_{13}}{2} \quad \{11\}$$

and P represents the mean 'pressure' of the residual stresses, corresponding to p , the 'volumetric' strain relaxation. Similarly, Q and T represent the shear stress components relating to the shear strain components q and t .

In this case, angle β may be computed via the following equation:

$$\beta = \frac{1}{2} \arctan(T/Q) \quad \{12\}$$

and the principal stresses can be evaluated by:

$$\sigma_{\max}, \sigma_{\min} = P \pm \sqrt{(Q^2 + T^2)} \quad \{13\}$$

For incremental drilling, the procedure for determining the residual stresses at a series of depth increments in a **uniform stress field** (as outlined in ASTM E837) is as follows:

- The sequence of relieved strains ε_1 , ε_2 and ε_3 and the corresponding hole depths are recorded
- The corresponding calibration constants $\bar{a}$ and $\bar{b}$ for the same hole depths are then determined from the tables provided
- The combination strains p , q and t and combination stress variables P , Q and T are then calculated
- Finally, the direction and magnitude of the principal stresses may be evaluated.

It has been noted previously that the *Equivalent Uniform Stress* method of data reduction does not work well in cases where residual stresses vary with depth. In order to determine whether stresses are distributed non-uniformly, all hole drilling must be carried out incrementally, recording strains at a number of hole depths. ASTM E837 contains distributions of strains that are relaxed during incremental drilling of Type A, B and C gauges in a uniform stress field. Accordingly, combination strains p , q and t are first calculated in accordance with equations {4}, {5} and {6}, and intermediate values are then re-calculated as % of the combination strain at the full hole depth (0.4 D).

ASTM E837 recommends that if the combination strains deviate from the given theoretical strain distribution by more than $\pm 3\%$, then the stress distribution should be treated as non-uniform and further calculation of residual stress data from the procedure given in ASTM E837 cannot be applied. In Measurements Group TN-503, the stresses determined by the equivalent uniform stress method (and subsequent calculation of ‘apparent’ equivalent uniform stresses) is considered to indicate the trend of residual stress distributions. However, **in the presence of significant stress gradients, the difference between the equivalent uniform stress and actual residual stress increases with each added depth increment.**

The Integral Method described in Section 6 recognises a fundamental feature missing from the EUS approach when evaluating residual stresses that vary with depth.

4 Current standard procedures and documentation

The main purpose of this Measurement Good Practice Guide is to provide the user with a simple, accessible document that provides practical guidance and advice for obtaining reliable and accurate hole drilling measurements. It is useful as a first step to review the currently available standard documentation, and highlight some of the omissions and differences between them.

Two key documents are currently in general use:

- ASTM E837-01e1: Standard Test Method for Determining Residual Stresses by the Hole-Drilling Strain-Gauge Method
- Measurements Group Technical Note TN-503: Measurement of Residual Stresses by the Hole-Drilling Strain Gauge Method

ASTM E837-01e1 [1] provides the user with a test procedure for determining residual stresses near the surface of isotropic linear-elastic materials. The current edition was approved in 2001 and published in 2002. Since the first issue of the GPG, there have been only small changes to the ASTM standard. Now published as ASTM E837-01e1 the document does not cover the Integral method, but this is due to be addressed by a separate standard in the near future.

Measurements Group Technical Note TN-503 [2] is also one of the most widely used industrial guides to the measurement technique.

Lu [15] also gives an excellent overview of the method, in a chapter on hole drilling in the *SEM Handbook of Measurement of Residual Stresses*, and the reader is encouraged to consult this reference in conjunction with this Guide and the two documents detailed above.

Table 1 compares the scope of ASTM E837-01e1 and MG TN-503 identifying some of the key differences between the two documents.

Recommendations	ASTM E837-01e1
Scope	Method for determining residual stresses near the surface of isotropic linear elastic materials, where the stresses do not vary significantly with depth and do not exceed 50% of the yield strength
Strain gauges	<i>Type A</i> – General Purpose  <i>Type B</i> – Assistance with obstacle  <i>Type C</i> – Large strain sensitivity and thermal stability needed 
Surface Preparation	As per manufacturers recommendations. A smooth surface is usually necessary for strain gauge application, although excessive abrading or grinding can noticeably alter the surface stresses.
Drilling techniques	<i>Abrasive Jet Machining</i> – Not suitable for soft materials such as Cu <i>High Speed Drilling</i> – Generally suitable except for very hard materials such as stellite <i>Low-Speed Drilling with Modified End Mills</i> – Some workers have reported success, but it appears that this is the least suitable method
Total depth and depth increments	$\geq 1.2D$ thick – increments of $0.05D$ up to $0.4D$ $\leq 0.4D$ thick – through-thickness test (1 set of strain values) ASTM standard does not cover those thicknesses between $0.4D$ and $1.2D$ – any tests should be recorded as non-standard Recommends 8 equal depth increments at constant intervals to $0.4D$, but states that other increments can be used
Yield Stress Criteria	Only applicable where the stresses do not exceed 50% of the yield strength
Stress computation for uniform stress fields	$\bar{a}$ and $\bar{b}$ calibration coefficients are tabulated. These values are derived from finite element studies. The averaging procedure is a specific case of the <i>Power Series Method</i> proposed by Schajer.
Non-uniformity	Scope does not cover methods for evaluating non-uniform residual stresses from incremental strain data ASTM E837-01 refers the reader to Ref 15
Drill Wear and condition	Not considered

Table 1: Scope and Details of ASTM E837-01e1

Recommendations	Measurements Group TN-503
Scope	Primarily for cases where the residual stresses are uniform throughout the drilling depth. Includes some analysis techniques (Equivalent Uniform stress method) and checks for interpreting non-uniform stress profiles.
Strain gauges	RE Gauge $\Leftrightarrow$ Type A  UL Gauge (same pattern as RE)  UM Gauge $\Leftrightarrow$ Type B  Does not consider Type C (six-gauge rosette)
Surface preparation	Refers the user to Measurements Group Bulletin B-129. Once again, caution is recommended re: excessive and over-enthusiastic surface preparation.
Drilling techniques	<i>Abrasive Jet Machining</i> – Principal advantage is that it can produce stress-free holes, but it's chief limitations are the considerable changes in hole shape as a function of hole depth - not generally recommended <i>High Speed Drilling</i> – Generally suitable <i>Low-Speed Drilling with modified end mills</i> – Generally suitable
Total depth and depth increments	Drill to 0.4D full depth. No guide given to increments, but the worked example uses increments of 2 x 0.005 in, 4 x 0.010 in then 1 x 0.020 in
Yield Stress Criteria	Only applicable where the stresses do not exceed 70% of the yield stress
Stress computation for uniform stress fields	$\bar{a}$ and $\bar{b}$ calibration coefficients are tabulated and plotted Residual stresses calculated using the <i>Equivalent Uniform Stress</i> (EUS) approach
Non-uniformity	Intended primarily for applications in which the residual stresses are uniform throughout the drilling depth Qualitative measurements of variation – by inspection of incremental EUS
Drill Wear and condition	Not considered

Table 2: Scope and Details of MG TN-503

4.1 Overview of ASTM E837-01e1

(Standard Test Methods for Determining Residual Stresses by the Hole Drilling Strain-Gauge Method)

The scope of the document covers those cases where the stresses do not vary significantly with depth and do not exceed one-half of the yield strength. It deals with both full depth and incremental drilling and uses the basic method of data analysis.

Only brief attention is given to specimen preparation, but attention is drawn to ASTM standard E251, ‘Test Methods for Performance Characteristics of Metallic Bonded Resistance Strain Gauges’ [16], which is a referenced document within the standard. The guidelines only state that the surface should be prepared as per the strain gauge manufacturers recommendations, but note that a smooth surface is usually necessary for strain gauge application, **and that excessive abrading or grinding can noticeably alter the surface stresses.** Several different drilling techniques are considered suitable for hole drilling, including abrasive jet machining, high speed drilling (up to 400,000 rpm) with an air turbine and lower speed drilling with modified end mills or carbide drills. **The standard suggests that abrasive jet machining may not be suitable for softer materials such as copper and high-speed drilling is generally suitable except for extremely hard materials such as stellite. It also states that low-speed drilling with an end mill may be less suitable than the other two methods.** Verification that the chosen drilling method does not in itself introduce residual stresses into the material is recommended by applying a strain gauge to a stress-free sample of the same composition. In practice however, this may be difficult, and is rarely carried out.

For incremental drilling, two procedures are suggested for choosing the depth increments, depending on the thickness of the sample. A specimen whose thickness is at least $1.2D$ is considered to be “thick” and in this case, it is recommended that eight sets of strain readings ϵ_1 , ϵ_2 , ϵ_3 , are measured as the hole depth is increased in equal increments of $0.05D$, up to a final hole depth of $0.4D$. Other similar depth increments are acceptable, but are less convenient as they would require additional interpolation or recalculation of the calibration constants. For a specimen with a thickness less than $0.4D$ (defined as “thin”), only one set of strain readings ϵ_1 , ϵ_2 , ϵ_3 , should be taken after a hole has been drilled through the entire thickness of the specimen. The ASTM standard does not consider the case where the specimen thickness is between $0.4D$ and $1.2D$, and it suggests that if either of the above methods are used in such a case, the residual stress results should be reported as “non-standard” or “approximate”.

One of the key issues in ASTM E837-01e1 is the way in which stress non-uniformity is handled. The document recommends that for thick samples, a test should be made to check that the residual stresses are uniform within the hole depth – by comparing the distributions of the experimentally relieved strains with the distributions for p and q or t , which are included in the standard. **If substantial differences in the relieved strain distributions (greater than $\pm 3\%$) are observed, the measured data is not acceptable for residual stress calculations using the procedure described.** Details of appropriate methods for evaluating non-uniform residual stresses from incremental hole drilling strain data are given elsewhere in this guide and in other reference work (Ref. 17), but such calculations do not fall within the scope of the ASTM test method. **The ASTM standard therefore is currently only applicable to uniform stress fields.**

4.2 Overview of Measurements Group TN-503-5

(Measurement of Residual Stresses by the Hole Drilling Strain Gage Method)

Measurements Group manufacture a wide range of strain gauges, and supply software, advice and instrumentation for strain gauge practice and analyses. Technical Note TN-503 [2], which is now available as an interactive document on the Measurements Group website, is an accepted reference document for the hole drilling technique, and in conjunction with the ASTM standard, is an important source of reference for this subject. As with ASTM E837, the basic scope of the document covers incremental hole drilling in uniform stress fields.

Examples are given where appropriate, often using proprietary Measurements Group equipment, but the information is of general use to all hole drilling practitioners.

It is noted that the following factors are considered to have most effect on the accuracy of the hole drilling method:

- Strain gauge selection and installation;
- Hole alignment and boring;
- Strain-indicating equipment;
- Good understanding of the mechanical properties of test material.

Surface preparation, an important issue discussed only briefly in the ASTM standard, is considered in greater detail in a dedicated Measurements Group Instruction Bulletin B-129-7 [18] entitled “Surface Preparation for Strain Gauge Bonding” (referenced within TN-503), providing the general procedure for surface preparation and bonding of strain gauges.

Accurate alignment of the drill is emphasised and a number of references are given [19-21] highlighting relevant experimental studies. To achieve the alignment, the document recommends the RS-200 Milling Guide (shown in Figure 2, along with other commercially available hole drilling rigs), which is also manufactured and supplied by Measurements Group. The milling guide is secured to the component being measured by bonding three feet with adhesive cement. A microscope with cross-hairs in the eyepiece is then installed in the unit and visual alignment and positioning of the central column achieved with the aid of four X-Y screws on the exterior of the guide to ensure that the drill axis coincides with the centre of the strain gauge rosette.

A key assumption of the technique covered in the Technical Note is that the material under investigation displays linear-elastic behaviour, and indeed, this is also an assumption of the ASTM standard. It acknowledges that if the stress/strain behaviour is non-linear due to yielding or other causes, the calculated residual stresses will be in error. Localised yielding due to the introduction of the hole may also occur if the initial residual stress is close to the yield strength of the material, and therefore the recommendation in the document is that measurements are only valid if the residual stresses present are below the threshold level of 70% of the yield strength. This compares to the 50% level suggested by the ASTM standard. **Neither documents specify explicitly that material property data is obtained from a separate mechanical property test, but this is recommended where possible.**

The need to drill to small increments of depth and determine the uniformity of the stress field is highlighted. The document notes also **that a nonuniform stress field invalidates the use of the full-depth coefficients $\bar{a}$ and $\bar{b}$, and in such cases, the calculated stress is always lower than the actual maximum. The graphical test outlined is not a sensitive indicator of stress field uniformity, but rather a means of identifying extremely nonuniform stress fields.**

The analysis method proposed in the document is referred to as the *Equivalent Uniform Stress (EUS)* technique. By definition, the EUS is that stress which, if uniformly distributed, would produce the same total relieved strain, at any depth, as measured during hole drilling. The statement is made that for the first small increment of depth, the calculated EUS is the best available estimate of the actual average stress in that layer, although less quantitative interpolations can be made with subsequent depths.

The hole drilling procedure and subsequent data reduction method outlined in TN-503 are suitable for uniform stress fields, and for these conditions the data reduction coefficients are well established and the calculated stresses are sufficiently accurate for most engineering purposes. The Technical Note also states that that little, if any, quantitative interpretation can be made of the incremental strain data for increments beyond $Z/D=0.2$, regardless of analysis technique, despite most practical measurements being carried out beyond this depth.

5 Practical issues associated with the measurements

There are two main issues critical to making good quality hole drilling measurements: the **practical issues relating to how the hole is introduced** and the quality and uncertainties associated with the strain measurements themselves, and **how the strain data is subsequently analysed** to give the information on residual stresses originally present.

The two areas will be considered separately in the following sections. Some of the practical issues are considered below, and recommendations on the analysis methods are given in Section 6.

The practical issues addressed in the following section include:

- Planning the measurements
- Strain gauge selection
- Surface preparation and installation
- Strain gauge instrumentation
- Alignment
- Drill and hole size
- Hole spacing
- Zero depth detection
- Selection of drilling increments
- Drilling
- Strain measurement
- Measuring the hole dimensions

5.1 Planning the measurements

The first and primary consideration in planning the hole drilling experiment is the suitability of the hole drilling method to the component under investigation. Hole drilling is a semi-destructive technique with relatively low sensitivity and other techniques may be more appropriate. It is, however, probably the least expensive and most widely used technique [3] for measuring residual stress.

Ideally, the material to be tested should be isotropic and the properties of the material should be known. **Experimentally determined values for Young's modulus (E) and Poisson's ratio (ν) should be used if possible, particularly for non-standard alloys and materials, where handbook data is not available.** Handbook values are only truly correct for well-defined, homogeneous materials. **Measurements Group TN-503-5 states that typical uncertainties in the mechanical properties of common steel and aluminium alloys are in the range 1-3% and as such only make a small contribution to the overall uncertainty in the measurement (see Section 8 also).**

The basic calculations for determining residual stress require that the stress distribution is uniform with depth and that the stresses should be less than 50-70% of the yield stress (see below). There are many circumstances where these requirements are not met, e.g. residual stress measurements on a shot peened surface, at a weld or close to a hole. This does not

necessarily mean that the hole drilling technique cannot be used, but consideration must be made for such effects. For example, welding processes generate large residual stresses that may reach and even exceed the yield strength of the base metal being welded, and in such cases the two principal sources of error are firstly from any assumption of uniformity in the stress field and secondly the plasticity around the hole – both of which are considered in more detail later.

One hole drilling effect that has been considered both experimentally [20,22,23] and analytically [20,24] is the possible error in residual stress measurements due to the effect of localised yielding. Plasticity in the region around the hole may induce an error if the magnitude of the stress around the hole exceeds the yield strength of the material. There is agreement among different investigators that the errors are negligible when the residual stresses are considerably lower than the yield stress of the test material. Lin and Chou [25] put the limit of this value at about 65%. They also found that when the applied stress exceeds 65% of the yield stress, the plastic error increased with increasing tensile stress, with maximum errors in the range 32-47% occurring when the tensile stress increased to 95% of the yield stress. **The ASTM standard states that the technique is only valid for cases where the residual stresses do not exceed 50% of the yield strength whilst the Measurements Group Technical Note suggests a limit of 70%.**

In practical terms, adequate access to the drill and gauge location is required. Ideally the sample should be flat with the hole location remote from any edges. In reality, tests often need to be conducted on curved surfaces or at a location close to an edge, hole or some other feature. In such cases the results may provide sufficient information but the validity of absolute levels of stresses from such installations must be considered carefully. In critical cases, significant departures from the ideal can be checked by using finite element models to calculate the $\bar{a}$ and $\bar{b}$ coefficients for the specific installation.

5.2 Strain gauge selection

In some of the earliest investigations of the hole drilling technique, and before the advent of the dedicated 3-gauge rosette, three separate uniaxial strain gauges were often used, installed and spaced around a small circle on the component. This approach is still possible, but there is little merit in doing so and it is not recommended, as it is extremely difficult to position the gauges accurately and can lead to large measurement errors. A number of commercial strain gauge designs are now available, designed specifically for the hole drilling technique. They come in a range of sizes, suitable for a wide variety of materials by matching of coefficient of thermal expansion. All of the rosette designs incorporate target marks for aligning the drilling tool precisely at the centre of the gauge circle.

The relieved strains depend on the stresses that originally existed at the boundaries of the hole. **The state of stress outside the hole boundary does not affect the relieved strains and the hole drilling method is thus a very localised measurement of stress.** The calculations of residual stress also assume that the variations of original stress within the hole area are negligible and can be ignored. The relieved strains fall rapidly with distance from the edge of the hole and the gauges typically only measure between 25-40% of the original residual stress present at the hole location. The residual stress values calculated from the single readings represent average values with greater weighting from material close to the surface reducing to zero at greater depth.

ASTM E837 describes 3 commercially available strain gauge designs, which were shown previously in Figure 1. Type A is recommended for general-purpose use, Type B for measurements near an obstacle, such as a fillet radius or weld, and Type C for situations where large strain sensitivity and high thermal stability are required. **The Type B gauge has a higher strain sensitivity (in the range +6% to +12%) compared with Type A.** Care should be taken if comparing raw strain readings from different users if the gauge types are not the same. The Type C, 6-gauge design consists of pairs of gauges with radial and tangentially aligned grid axes. The opposite pair of gauges (eg 1T and 1R in Figure 1) should be connected as a half bridge. **For the Type C gauge, this arrangement offers increased sensitivity (in the range +70% to +140%) over conventional gauge layouts.** Disadvantages of using these gauges include the higher cost, limited availability, and the extra preparation time and instrumentation associated with the 6 gauges (*connected to 3 channels*).

Individual strain gauge manufacturers use their own coding system but most have variations on these designs, covering a variety of sizes and hole diameters with temperature compensation appropriate to a range of common materials (examples given in Table 3). **The reader is recommended to purchase good quality gauges (for which the calibration coefficients are readily available) from a reliable supplier, and use recommended strain gauge installation procedures as the stress values measured are strongly affected by the quality of the installation and expertise of the user.**

Manufacturer	Gauge	Hole dia/depth	Type
Measurements Group	EA-xx-031RE	0.6 – 1.0	A, open
	EA-xx-062RE	1.4 – 2.2	A, open
	EA-xx-125RE	2.8 – 4.4	A, open
	CEA-xx-062UL	1.4 – 2.2	A, encapsulated
	CEA-xx-062UM	1.4 – 2.2	B, encapsulated
	N2K-xx-030RR	1.4 – 2.2	C, open
HBM	RY21	?	?
	RY61	1.4 – 2.2	?
	VY61	1.4 – 2.2	?
TML	FRS-2	1.4 – 2.2	?
	FRS-3	2.8 – 4.4	?

N.B. This table is provided for information only and is not an endorsement of a particular strain gauge supplier.

Table 3: Details of the more commonly available residual stress gauges

The primary factor to be considered in gauge selection is size. This is most important because of the direct relationship between gauge size and :

- The size of the available target area (proximity of edges, weld features, etc)
- The required stress integration area; smaller gauges use smaller drilled holes over which the residual stress results are integrated

- The depth to which the residual stress data is required; larger gauges produce deeper stress data whereas smaller gauges are best for fine, ‘near-surface’ work.

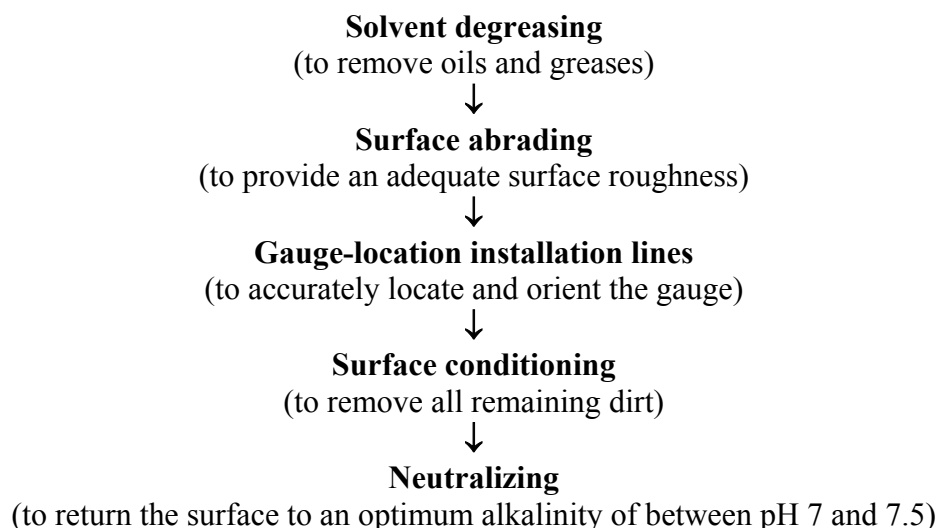
Only a limited range of gauge sizes are available, with the “062” designation the most popular choice. This refers to the individual gauge length of 0.062 inch or approximately 1.57mm. This size of gauge is capable of providing useful residual stress data to a depth of approximately 1 mm.

It should be noted that the experimentally generated errors associated with the measurements from small strain gauges (accuracy of hole drilling, control of depth etc.) are likely to be higher than the corresponding measurements with larger gauges. However, the largest available gauges also require careful handling and the measurement procedure is likely to take significantly longer because of the sizes of drills required and large amount of material to be removed during the drilling process.

Other factors that should be considered in selecting the most suitable strain gauge include the ease of handling, availability, cost, preferred supplier, temperature compensation, etc. Encapsulated designs are available which come complete with solder tabs, connection wires or cables, making them particularly suitable for use in rough environments where special protection for the gauge is required. Conversely, ‘open’ format gauges are more adaptable to installation on irregular surfaces where the stiffness of encapsulating layers resists conformance to the surface contour.

5.3 Surface preparation and installation

Installation of the strain gauge rosette should be carried out by qualified personnel in accordance with the manufacturer’s instructions, as **the quality of the installation has a direct influence on the quality of the strain readings measured**. To ensure a good bond between the strain gauge and the component, the surface must be properly prepared. The surface should be chemically clean, have an appropriate surface roughness, and have neutral surface alkalinity corresponding to pH7. The steps of the process as recommended in Measurements Group Bulletin [18] are as follows:



Measurements Group Tech Note TN-503 [2] reiterates that the surface preparation and installation procedures be of the highest quality. This is particularly important in fine-incremental hole drilling as the strains measured are generally quite small (typically only several $\mu\epsilon$ in the first depth increment), and considerably lower than those measured in a conventional mechanical test at the same stress level.

The key to surface preparation is to develop a suitably rough surface necessary for strain gauge application without appreciably altering the state of the surface stresses. **Measurements Group Instruction Bulletin B-129-7 [18] suggests a surface finish (Ra) of between 1.6 and 3.2 μm for general stress analysis and this will be adopted for the installation of residual stress gauges in this Guide.** The roughness of the surface is an important consideration in fine increment hole drilling as the first depth increment (and first residual stress measurement) may be of the same order as the height of the asperities.

Extensive studies have been carried out by Prevey [17] to examine the residual stress and cold work distributions produced by five methods of abrasive surface preparation on a stress-free steel, using X-ray diffraction and electropolishing. The mechanical abrasive techniques appear to induce additional stresses that can alter the residual stress distributions produced by machining, grinding or shot peening, the same stresses that may be the subject of study. Mechanical surface preparation methods may also induce a cold worked layer, the magnitude and depth of which will be a function of the severity of the treatment. An immediate consequence of this is the possibility of local yielding of the surface layer to which the strain gauge has been bonded. Yielding and the resulting non-linear strain response will cause significant error in the residual stress calculated and these are not readily detectable from the strain readings. Prevey even suggests that mechanical abrading should be avoided as much as possible if incremental hole drilling is to be used to study the near-surface stresses in a material. Hampton and Nelson [26] established similar results to this in 1992.

It is important to point out that the differences observed above are only apparent over a very shallow range of depths, and their importance depends on the residual stress gradients and the measurement requirements. Where the component contains a uniform stress distribution, the influence of induced stresses due to surface preparation are less important than specimens that exhibit sharp near-surface stress gradients. For example, a 'surface' stress of 100 MPa decaying to zero at 10 μm would produce an apparent stress of approximately 4 MPa when averaged over a 125 μm first increment. **If near-surface measurements are required then it is most likely that the abrasion technique will influence the accuracy of the first increment measurement. Beyond the first increment, however, the degree of abrasion is less likely to influence the results.**

For many materials, mechanical methods of surface preparation can be avoided by the use of a localised etching process. Suitable etchants are available for most ferrous and non-ferrous metals. These can be applied to the target area using a small 'dropper' or as a swab etch. The surface finish obtained by this process will be dependent upon the structure of the material and its interaction with the etchant. In many cases the surface finish is smoother than that noted above, however, the finish is usually matt in appearance and capable of providing an effective anchor for the strain gauge bond. When using dilute acids, etching times may be reduced by a small increase in the specimen temperature. As part of the material handling precautions, it is recommended that an intermediate neutralization of the surface should be carried out immediately following the etching process.

The simplest and most common method of bonding the strain gauge to the specimen is using a conventional cyanoacrylate adhesive. These adhesives consist of a single component with a relatively short cure time (1-2 mins), and are relatively easy to handle and use. Other adhesives are available but consideration must be given to cure time and temperature and to achieving a creep-free bond. If the surface of the component is particularly rough, it is important that the chosen adhesive adequately fills the asperities and irregularities to achieve a good bond. In such cases, a more viscous, 2 component epoxy adhesive may be more suitable. It is also to be noted that extremely rough surfaces are also to be avoided because of ambiguity when attempting to establish a 'zero' or 'datum' depth for incremental drilling.

Other considerations may be significant during gauge installation :

- For field installations, surface scale, rust or paint should be removed if at all possible and standard surface preparation procedures followed. The speed of installation may necessitate the use of cyanoacrylate adhesive.
- In extremely large components, in field installations, or where some local heat application has been required to achieve gauge adhesion it may be necessary to consider the effect of component temperature. Monitoring changes in the gauge output after installation and instrumentation can assure the operator that a steady state has been achieved and that spurious thermal stresses are not included in the results.
- The gauge backing material may be trimmed or slit prior to installation so that less critical parts of the layout (grid to tab conductors) may be accommodated around fillets or other features that would otherwise result in severe curvature of the gauge. Integrity of installation of outer parts of the rosette layout may be compromised for the benefit of the gauge element areas.

5.4 Strain gauge instrumentation

It is important that the instrumentation chosen for strain measurement is calibrated and 'fit for purpose'. This means that a variety of systems may be used provided that the basic requirements for individual strain measurements are met. Some of the key factors that must be considered in making a selection include accuracy requirements, the number of simultaneous strain channels required, the availability of equipment and budget restrictions.

ASTM E837 stipulates that the instrumentation for the recording of strains shall have a strain resolution of $\pm 2\mu\epsilon$ and that the stability and repeatability shall be the same, but most modern instrumentation should be able to resolve to $\pm 1\mu\epsilon$ and this should be regarded as the benchmark level. The stability, resolution and accuracy of the strain measurement instrumentation is particularly important for reducing the uncertainties and scatter in fine-increment drilling where, in the first few increments, very small strain levels are being measured. It is also recommended that the wires should be as short as practicable and that a three-wire temperature-compensating circuit should be used. Generally, most modern strain gauge instrumentation has the required resolution and stability for measuring the small strains in incremental hole drilling. Both portable and laboratory-based systems are commercially

available, and provided the chosen system is regularly calibrated, most are suitable for hole drilling as there is no requirement for a very fast acquisition rate.

The use of a strain gauge amplifier with carrier frequency (AC) excitation is also recommended by a number of industrial suppliers. This offers greater measurement stability against possible temperature fluctuations, particularly within an industrial environment. However, the potential errors are of secondary consequence in comparison with many of the other practical issues outlined here.

Before proceeding there are two further checks that can be made to validate the integrity of the installation. If possible a small mechanical loading can be applied to the sample and the strain readings before and after loading noted; if the gauge installation is good there should be no hysteresis or difference in the gauge readings, and the strains should return to zero after the load is removed. It is also recommended that a visual inspection of the gauge installation be carried out, as areas that are not well bonded often show up. In such cases the gauge should be removed and the installation repeated.

5.5 Alignment

Even small levels of eccentricity and misalignment between the centre of the drilled hole and the target of the strain gauge rosette can introduce significant error into the measurements of residual stress, so these should be minimized. Wang [21] tried to quantify the error due to misalignment, by examining the alignment error in both a uniaxial-stress field and a hydrostatic-stress field. The error analysis showed the result that 10% of hole radius off-centre gave about 5% measurement error for a standard Type RE rosette. **ASTM E837 states that the centre of the drilled hole should coincide with the centre of the gauge to within either $\pm 0.004 D$ or $\pm 0.025\text{mm}$, whichever is greater.**

It is important, therefore to ensure accurate alignment prior to drilling by the use of a suitable alignment device. Typical arrangements include the use of a travelling microscope, a digital x-y stage or an optical microscope. It is also vital that the drill is aligned perpendicular to the surface of the component. This can be a significant practical issue, particularly for measurements in the field. Commercial portable drilling devices usually have a means of adjusting the vertical alignment and perpendicularity, such as adjustable feet. Spirit levels, gauge blocks and dial gauges can be used to check, set and determine the perpendicularity. **It is crucial that the user examines the experimental set up for possible errors as a result of off-axis alignment before each test.**

Measurements Group Tech Note TN-503 [2] states that the RS-200 milling guide has a precision of $\pm 0.025\text{mm}$, and this equates to an error in the calculated stress of approximately 3% for a uniaxial stress state. With this instrument, a microscope is installed in the unit and visual alignment is achieved with the aid of four X-Y adjustment screws on the exterior of the guide. The equipment supplied by HBM is similar in design – a cross-hair in the ray path of the optical system is made to coincide with the positioning marks on the rosette. The drill is then locked in a simple manner in the optical axis.

Accurate alignment is crucial to achieving a good measurement. Ensure that the drill is centred precisely at the centre of the strain gauge rosette using an appropriate technique.

Users can ensure that the drill is perpendicular to the specimen surface by exploiting the features of the drilling apparatus. In drilling a 2 mm diameter hole in a 062 size target gauge, a 1° inclination from the perpendicular would result in a depth differential of 17 µm between the ‘leading’ part of the drill and the drill centre. This corresponds to a substantial error in depth in a (typical) 125 µm increment, and a greater effect with a typical fine-increment of 10-30µm. Its effect will also depend on the orientation of the inclination axis to the rosette layout.

5.6 Drill and hole size

The maximum recommended hole diameters are generally provided with the hole drilling strain gauge datasheet and depend on the gauge circle diameter. **ASTM E837 recommends a minimum hole diameter of 60% of the maximum allowable diameter.** In general, larger holes are recommended because of the higher magnitude strain readings and increased strain sensitivity achieved. A typical drill diameter of about 1.6mm to 1.8 mm is used for a “062” MG UL-type gauge, but if orbital drilling is used (see later), the hole diameter will of course be significantly larger than the drill diameter. It is worth noting that as the ratio of D_o/D increases, the sensitivity of the method increases in approximate proportion to $(D_o/D)^2$.

Figure 4 shows a selection of drills that can be used with the conventional sized gauges.

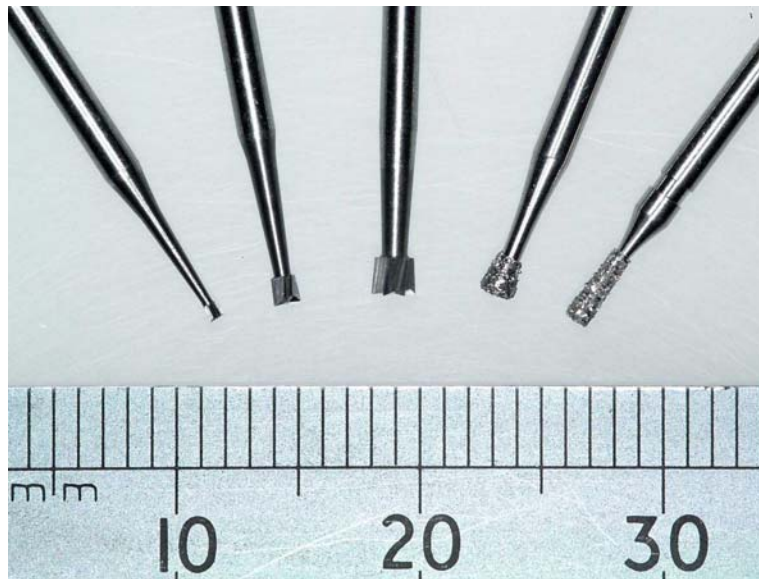


Figure 4: Selection of drills

The recommended drill suitable for most materials is the inverted cone tungsten carbide type. The cutting edge of the drill must be flat or slightly concave; the side relief of the inverted cone gives clearance for chip removal without impact on the cut surface. The sharp corner at the outside of the cutting edge produces the required hole profile; a chamfer or radius is not acceptable. A wide range of drill sizes (0.6 mm to 2.3 mm diameter) are available with 1.6 mm or 2.3 mm shanks (to suit motor collets); long and extra-long series drills are useful for installations close to shoulders where access is difficult. **Drills should be subjected to a brief visual inspection (x3 eyepiece) prior to use and discarded after use in drilling one hole.**

For hard materials (carburised and nitrided steel, ceramics, glass, etc), diamond impregnated inverted cone drills are available. This drill type cannot ‘cut’ at the centre of rotation and requires to be used with an ‘orbital’ motion whereby the drill is slowly rotated about an axis parallel to the axis of drill rotation, typically with an eccentricity of 0.2 mm to 0.5 mm. **Diamond impregnated cutters do not cut a hole with a ‘sharp’ corner; the small corner radius represents a departure from the ideal case for which coefficients have been evaluated. In such cases, the residual stress data from near-surface increments should be treated with caution.** A more detailed discussion of drill sizes and hole shapes follows in Section 5.10.

For ultra hard, difficult materials, wear resistant and treated surfaces laser drilling could be used to produce the hole, but no commercially available hole drilling rig is currently available with this option. Drilling could be carried out at the laser drilling facility, if portable instrumentation is available to record the strain data.

5.7 Hole spacing

The ASTM standard does not contain any recommendations relating to the minimum distance between adjacent holes, but the Kirsch solution [27] for stresses at through-holes indicates that little interaction effect between holes would be expected for holes six or more diameters apart. Hampton and Nelson [26] studied the effect of hole spacing in 1992. Calibration studies using UM-type gauges on a 5.18mm thick stress-relieved steel sample showed a difference of 7% in the maximum computed stress when the centres of two adjacent blind holes were spaced 4.5 hole diameters apart. Further studies established a stress difference of less than 1% when they were placed 5.7 hole diameters apart.

It is recommended therefore that the minimum distance between holes should be at least six hole diameters. Where possible, gauge elements should be located away from (rather than between) adjacent holes.

5.8 Zero depth detection

One of the most important issues relating to the practical measurement of shallow residual stress profiles and the variation of residual stress with depth (using the incremental technique) is the accurate detection of the zero (or ‘datum’) depth, i.e. when the gauge backing and adhesive have been completely removed, the drill is first in direct contact with the surface and the strain reading are set to zero. This is even more important with the fine-increment approach as uncertainties in defining this position can strongly influence the calculation of stress in the first increment. In such cases the uncertainty in defining this position can be of the same order as the surface roughness and the issue in this case is how the surface is defined – is it when contact is first made at the tip of the asperities, or the mean of the peak to peak roughness variation? Neither ASTM E837 nor the MG TN 503-5 considers this issue in any detail. Figure 5 below shows a surface roughness profile from an aluminium sample that has been prepared ready for strain gauging. The vertical scale of the surface profile is highly magnified compared to the horizontal axis, but it is clear that the typical peak to peak height is ~10-15 μm , which is of the same order as the first depth increment used in the fine-increment drilling.

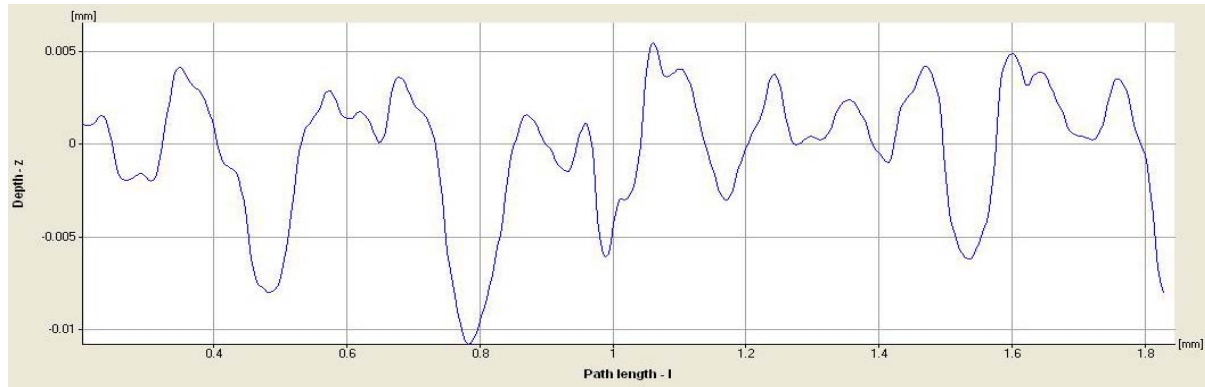


Figure 5: Typical surface roughness profile after preparation for gauging

Prior to starting the drilling programme, the drill should be lowered slowly so that the backing film on the strain gauge can be removed, but the drill should not make contact with the surface below. The “zero depth position” can be defined as the point at which the entire gauge backing has been removed, and the drill is in direct contact with the component surface without significant material removal. To reach this position, a number of problems can occur:

- There is the uncertainty of cutting through the thickness of the gauge backing material (plus any additional encapsulation)
- The surface roughness of the hole area will cause uncertainty in detecting a ‘unique’ zero depth over the hole area
- Any error in drill alignment (from the perpendicular) will lead to initial contact at one side of the hole
- A concave profile at the drill cutting edge may result in an initial ‘ring’ contact around the drill circumference rather than over the entire frontal area (this is acceptable because the depth of the drill corner gives the zero depth position)
- Axial clearance in drill motor bearings (in particular those of air turbines) may give rise to some ambiguity in the absolute position of the drill cutting edge.

All these potential problems can combine and contribute to a serious degradation in the quality of the stress data in the first, second and (to a lesser extent) subsequent depth increment. **Such errors cannot be detected or resolved by inspection of the strain data.**

A number of further observations can be made regarding the removal of the gauge backing. Electrical contact detection is sometimes used for detecting when the gauge has been broken, but this is not always feasible because many air turbine bearings do not conduct. Operator skill is often involved, and many practitioners who use air turbine drills rely on the change in tone of the motor to indicate the increase in load being applied to the motor as the extremities of the drill cutting edge begin to make contact with the harder component after cutting through the gauge backing.

Operators are encouraged to carry out oblique observation of the drilling process through a mini-video camera, magnifying eyeglass, travelling microscope or telescope. The device should be held close to the drill and the reflection of light from the gauge backing, provided by a suitable, well-directed **cold light source**, monitored as the gauge gets gradually thinner, finally breaking through onto the component. Figure 6 shows two pictures of the setup with the drill partially through the strain gauge backing, and after complete removal of the gauge and adhesive.

This simple, observational technique is inexpensive, easy and offers an accurate determination of zero depth. In practice however, the initial break is seldom 100%, and even from the remnant of adhesive remaining at first breakthrough small errors in perpendicularity and drill end concave profile can be detected.



Figure 6: Stages of removing the gauge backing to reach the zero depth surface

For any in-situ inspection both prior to and during drilling, it is important to use a cold light source – i.e. one that does not generate significant heat – as the use of conventional inspection lamps can introduce considerable thermally generated strains in the gauge and even heat the component surface. Improper illumination can introduce large errors and drift in the strain readings if not considered.

5.9 Selection of drilling increments

The exact sizes of increments may be pre-set by the hole drilling equipment or the requirements of the data to be input into the stress calculation software. The residual stress information required from the hole drilling procedure can play a part in the selection of sizes of drilling increment. In most instances, the hole is drilled in a large number of increments and the resulting strain data subjected to some form of smoothing process prior to the evaluation of residual stresses at a smaller number of calculation increments

If the test is to be performed to determine the level of residual stresses away from the surface, then between 8 and 14 increments may be sufficient to give the required detail. For a MG 062 size gauge, this could lead to a typical combination of depth increments from 128 μm , 256 μm and 512 μm , to a final hole depth of 1.40 mm to 1.60 mm, as recommended by ASTM E837. To obtain a greater level of detail in the near-surface region, it is necessary for hole drilling to proceed with a larger number of smaller near-surface increments.

For fine increment drilling, where the focus is in the near surface information, a typical drill increment of 10-30 μm is often used, and in these cases a high degree of control of the drill head is required to avoid significant depth errors. This is probably best accomplished using

some form of motor control rather than a manual / micrometer device. Drilling systems using a stepper motor / ball screw feed system can achieve reliable depth increments of 20 μm or less, although 30 μm to 40 μm may be regarded as a more reliable figure.

Once the fine increment strain data has been recorded it can subsequently be reanalysed using the strain values at the larger increments corresponding to the conventional approach. In this case the general stress profiles will be similar in shape, but differ in the level of near surface detail (see Section 6.3, Example 5). Section 6 deals further with the impact of the drilling and calculation depth increments on the calculation of residual stresses using the Integral Method.

5.10 Drilling

Several drilling techniques have been investigated in the literature and have been applied to hole drilling, and two important factors should be considered regarding the production of the hole. The first is the propensity of the technique for introducing additional stresses during the machining process, and the second is the ability of the technique to produce geometrically well-defined holes.

Conventional low-speed drilling was the first technique used for hole drilling measurements. Rendler and Vigness pioneered the technique of low speed drilling with specially developed end mills in 1966 [7] and modified end mills are now the preferred option. High-speed drilling techniques were first used by Flamann [9], using an air turbine drilling system rotating at speeds of up to 400,000 rpm. The typical drill used is a tungsten-carbide inverted-cone dental burr. Disadvantages with this system include:

- Damage to the bit can occur in very hard material, even before the first hole has been drilled.
- The very high speeds involved result in a low torque system, which can lead to the drill stalling and sticking.
- Backlash in the closely spaced bearings, which can result in large uncertainties related to the location of the cutting edge and a risk of whirl when using extended drills.

Abrasive jet machining has also been used as a means of minimising the stresses induced by machining the hole. The method was subsequently developed by Beaney and Proctor who used an orbiting head system that forms the basis of the technique in common use today. In the process, very fine cutting powder is blown through small diameter nozzles by compressed gas using a rotating jet. The abrasive technique has the advantage of being relatively quick and portable, but the main disadvantages and concerns are related to control of the hole shape and the limited depth control for accurate incremental measurements. **Abrasive jet machining is not recommended for the incremental hole drilling covered in this Guide.**

Electrical discharge machining (EDM) and Electro-chemical machining (ECM) can be used for drilling holes in electrically conducting materials. However, stresses in the surface layers and the requirement for gauge protection have prevented significant further development in these areas. For components that can be measured in the laboratory, a conventional milling

machine offers a stable, stress-free drilling technique that can be extended to drill large holes. The use of a speed multiplier also offers a wide range of drilling speeds (300 to 15,000 rpm).

Flaman and Herring [28] studied four different drilling techniques, which were quantitatively compared on the basis of induced stresses, hole geometry and controllability, and qualitatively on the basis of portability and ease of use. Results showed that low-speed, modified end milling was the only technique to induce high stresses and was therefore considered unsuitable for general centre-hole drilling. High-speed drilling was considered suitable for most materials examined, except extremely hard materials.

The calculation of residual stresses via any of the available techniques assumes a clean hole with parallel sides and a flat bottom. In practice this is not always the case. High-speed drilling is most likely to produce a circular, straight-sided and flat-bottomed hole provided an appropriate cutter profile is used. Low-speed cutting with a modified end-mill has also been examined from the perspective of hole geometry and appears suitable for most applications, although tapered sides have been observed in some cases [15]. One of the major limitations of the air-abrasion technique is the resulting hole geometry, which tend to have tapered sides and an irregular bottom profile, and it is difficult to accurately measure the correct depth. It is very difficult to control the size, shape and dimensions of the hole produced by electro-chemical milling; it has been shown to produce a symmetrical, but round-bottomed hole, which adversely affects the stress calculations.

Figure 7 shows sectional profiles through a series of holes at different depths to illustrate the typical development of the hole shape. Holes were made at 20 μm intervals. Unfortunately some of the section profiles were not taken across the exact centre of the hole so appear of a different diameter, but it is interesting to note the shape of the hole in the first few increments, which is affected to some extent by the original profile and roughness of the specimen surface.

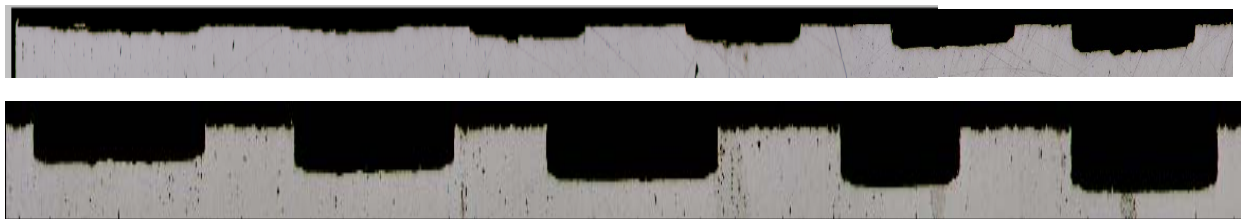


Figure 7: Cross sections through a series of holes showing the development of the hole profile

Another technique available is orbital drilling or trepanning. Here, the drill is deliberately offset from the centre of the gauge and the hole drilled with an orbital motion as shown schematically in Figure 8. This cutting action reduces the forces and heat output during drilling, which in turn, results in more stable strain readings. It permits the use of smaller drills, and the reduced cutter wear also enables the hole drilling method to be applied to harder materials (for example, nitrided and carburised surfaces) using conventional tungsten carbide cutters. Figure 8 shows a schematic of the orbital drilling process and a photograph of a full depth hole produced by this method. The hole is very clean, with a flat bottom and

straight sides. Both the final machining marks made by the orbital action of the drill at the bottom of the hole and the grain structure of the material is clearly visible.

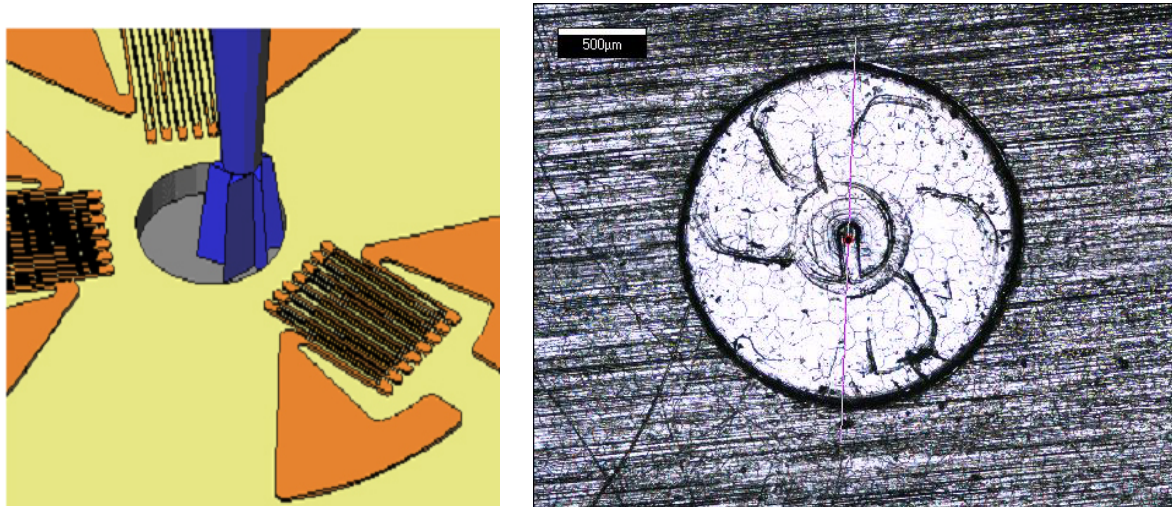


Figure 8: Schematic of orbital hole drilling (picture courtesy of Stresscraft Ltd.) and the resulting hole

Figure 9 shows the corresponding hole profile from a hole produced by orbital drilling.

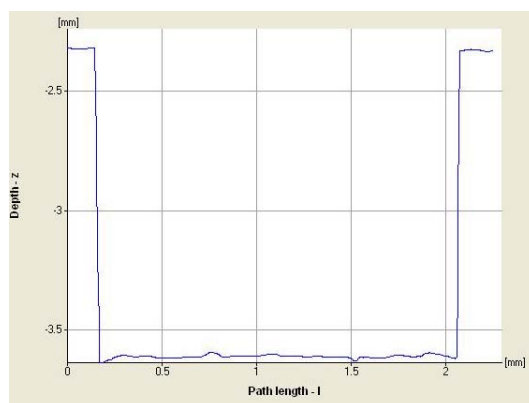


Figure 9: Representative hole profiles from tests using orbital drilling and a tungsten carbide end mill

Specific advice on drill wear is not included in either ASTM E837 or MG TN-503-5 yet this is one of the key issues affecting the quality of the hole shape. Excessive drill wear will be evident as the drill will not make progress through the component (not without losing depth setting in the air turbine set-up). Drills should be carefully examined on completion of drilling of the hole. Wear (flat or rounding) of the cutting edges should not be excessive. Wear or chipping at the drill corners may indicate insufficient stiffness of the drill mounting or excessive bearing clearance.

It is essential that a new drill be used for each measurement. If, during the drilling of a hole, the rate of feed is reduced to such a slow rate that the hole cannot be completed, then it is recommended that the hole and gauge be abandoned. The condition of a drill which leads to an unacceptable rate of progress (at speeds of up to 400,000 rpm for an air turbine) is also

unlikely to create a ‘stress-free’ boundary at the hole surface as required by the hole drilling method.

5.11 Strain measurements

Prior to the start of the hole drilling process, it is recommended that the drill (if the air-turbine type) is run for a period of time and then switched off while monitoring the strain gauge outputs. Any effects of the turbine exhaust passing over the gauges can then be observed. This may be useful when the air supply is at a different temperature to the component ambient and a suitable ‘settling’ period for gauge readings is required.

During the drilling process, strains for each gauge are recorded at the required drilling depth increments. It is usual for some heat to be generated during the drilling process, leading to localised thermal loading of the gauge area. Observation of the decay of transient thermal strains is necessary (particularly in thinner, poor conductors) so that a steady gauge output is obtained. This may take between 10 and 60 seconds with air-turbine drilling, depending on the component material and shape and air temperature noted above. **It is also recommended that the drill be retracted from the hole by 0.1 mm to 0.2 mm, and turned off while strain measurements are being recorded.**

Figure 10 shows the strain readings captured throughout a stage of the incremental hole drilling process.

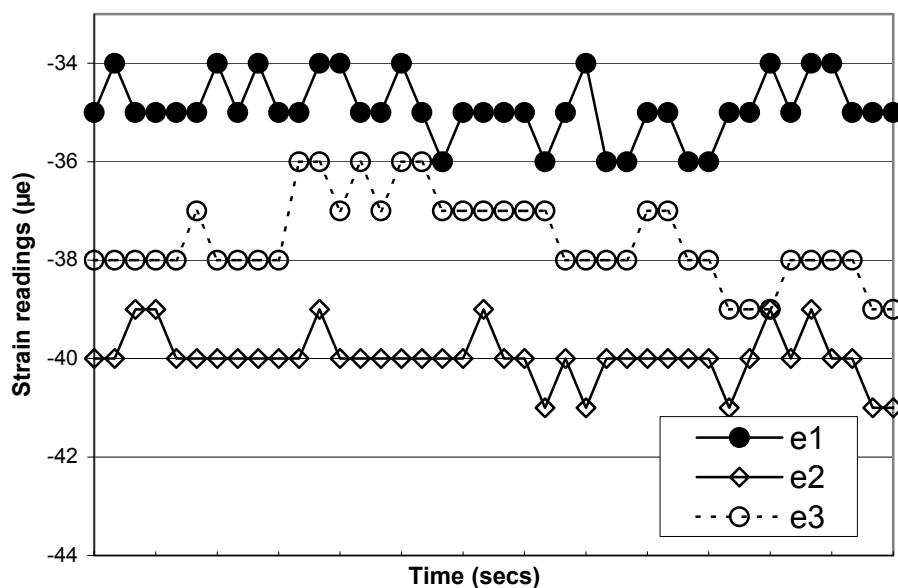


Figure 10: Typical variation of strain readings over time during data capture phase (data capture freq=1 Hz).

Although the gauge readings are not drifting there is a typical variation of $\pm 1 \mu\epsilon$ in the values, which probably reflects the resolution of the gauge instrumentation. If appropriate the readings can be stored in a datalogger and averaged over a set period of time, but there is little advantage to quoting the average strain data to fractions of a $\mu\epsilon$, and it is normal

practice to use integer values of the strain, which are either rounded up or down to the nearest value.

If the strain gauge readings continue to vary over time (this has been observed in some viscoelastic polymers, but generally not with the metallic materials covered in this guide) this might be an indication of problems with the gauge installation and the set up should be checked and, if necessary, the measurement discarded and repeated.

5.12 Measuring the hole dimensions

Most proprietary hole drilling equipment (MG and HBM) includes an optical head, which is used for:

- Drill alignment (via cross wires aligned with the gauge target features), and
- Measurement of the hole diameter against an optical scale graticule

Optical scales are supplied for direct reading in mm or inches or in arbitrary units requiring calibration against a standard scale.

After completion of the hole drilling process, the drilling head should be completely removed from the drill rig and replaced by the optical head. The gauge should then be inspected to confirm concentricity of the hole and target pattern, and any eccentricity recorded. It is usual for the cut edge of the gauge backing material to be irregular in nature. The gauge lead wires should then be unsoldered and the gauge removed from the component. With the use of a scalpel, the gauge can often be removed in one piece and retained with the strain data sheet to provide an additional record if required. The diameter of the hole should then be measured in two directions to an accuracy of 0.01mm using the optical head and graticule or remotely on a travelling microscope; the overall hole shape may be judged for any irregularities.

After removal of the gauge, the final hole depth can be measured using a conventional depth gauge, instrumented microscope or profilometer. Any departures from the expected hole depth (set during drilling by the drill rig micrometer) should be investigated. Drill wear, drill shank collet grip and drill rig/component mounting stiffness can all play a part in hole depth errors.

6 The Integral Method

6.1 Basic Approach

In Ref [12], Schajer proposes two methods for dealing with non-uniform stress distributions - identified as the *Power Series Method* and *Integral Method*. Part 2 of Ref [12] deals with the practical application of the Integral Method and presents all the necessary equations, coefficients and interpolation schemes required to produce a satisfactory program to perform the calculations. This is described in more detail below, together with a series of examples relevant to the application and issues associated with the method in Section 6.3. Details of a recent UK hole drilling intercomparison exercise, highlighting the importance of appropriate analysis techniques is summarised in references [29] and [30].

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 stratum 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 the surface strain changes to residual stresses for each of the stress depth and hole depth combinations shown in Figure 11. This example is given for four calculation increments for the $\bar{a}$ coefficients; the $\bar{b}$ coefficients are arranged and calculated in a similar manner.

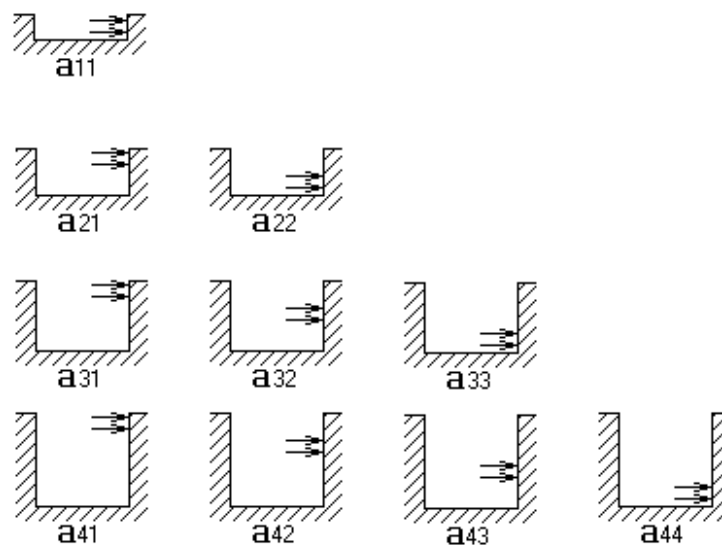


Figure 11: Hole and stress depths corresponding to coefficients $\bar{a}$

To calculate the residual stresses from the relaxed strains, Schajer [12] proposes the following steps :

- The hole should be produced at many small drilling increments so that the resulting strain data can be smoothed or filtered to reduce noise.
- At a smaller number of calculation increments, combination strains p , q and t are calculated from the smoothed strain data.
- Cumulative strain relaxation functions (A and B) for the measured hole diameter are calculated, by interpolation, from the sets of triangular matrices given in Ref [12].
- Coefficients $\bar{a}$ and $\bar{b}$ are calculated directly by subtraction of adjacent elements in the cumulative strain function matrices.
- Stresses P , Q and T are calculated for successive increments using the relationships:

$$\bar{a} P = p E / (1 + \nu) \quad \{14\}$$

$$\bar{b} Q = q E \quad \{15\}$$

$$\bar{b} T = t E \quad \{16\}$$

For example, the combination pressure stress ‘ P ’ is calculated over the first three increments, thus:

$$\begin{aligned} P_1 &= [p_1.E / (1 + \nu)] / \bar{a}_{11}, \\ P_2 &= [p_2.E / (1 + \nu) - (P_1.\bar{a}_{21})] / \bar{a}_{22}, \\ P_3 &= [p_3.E / (1 + \nu) - (P_2.\bar{a}_{32}) - (P_1.\bar{a}_{31})] / \bar{a}_{33}, \text{ etc} \end{aligned}$$

Combination stresses Q and T are calculated in a similar manner (but exclude the Poisson’s ratio term).

- The required stress outputs at each calculation increment ($\sigma_{\max}$, $\sigma_{\min}$, β etc) are obtained from the corresponding combination stresses as above.

6.2 Practical Considerations

The main advantages and limitations of the Integral Method include the following:

- **The Integral Method is able to decode relaxed strains that relate to highly non-uniform residual stress distributions.** For example, by using suitable drilling and calculation increments, residual stress distributions close to the surfaces of shot-peened components can be determined. Such distributions may include extremely intense near-surface compression followed by a rapid decay to a small sub-surface tensile peak.

- **The relationship given in the previous section shows how the stress term P_n is used in the calculation of term $P(n+1)$.** This coupling of calculations in successive increments produces the effect whereby, if strain measurement or depth errors combine to produce (for example) an overestimation of stress in increment n , the reuse of this stress term leads to a corresponding underestimation in increment $(n+1)$. The consequential effect on the stress in increment $(n+2)$ is very small.
- **The number of calculation increments that can be supported depends on the quality of the experimental data. Five or six calculation increments yield a satisfactory level of detail for many stress distributions.** If this number is significantly increased, then residual stresses between successive calculation increments may be seen to oscillate about the original stress level. Excessive ‘smoothing’ of strain data to reduce oscillation (to permit the use of smaller stress calculation increments) is unlikely to reveal a significant increase in ‘true’ stress distribution detail, especially towards the full hole depth.
- **The sensitivity of the hole drilling method reduces with hole depth.** This is not a feature of the Integral Method, but rather a reflection of the fact that, as the hole depth increases, the stress change caused by material removal is located further from the strain sensor. This limitation is more severe for $\bar{a}$ coefficients than for $\bar{b}$ coefficients so uncertainties in the average values of principal stresses are usually greater than uncertainties in differences between principal stresses.
- **The reduced sensitivity with hole depth is addressed by increasing the size of calculation increments at greater depths.** Zuccarello [31] has developed a scheme for optimising the distribution of depth increments by minimizing the influence of strain input errors on the calculated stresses. Alternatively, a scheme can be adopted which is based on convenient depth increments. For example, 5 calculation increments for use with MG 062 size gauges may consist of 2 increments of 128 μm , then 2 increments at 256 μm followed by a final single increment of 512 μm . This would require a hole depth of approx. 1.4 mm produced by 11 x 128 μm drilling increments (depending on the strain smoothing scheme). By comparison, if the near surface stresses were of particular interest a fine increment approach might use 4 increments at 32 μm , followed by 4 at 64 μm and 8 at 128 μm to the same final depth.

6.3 Examples and Issues

A number of examples are included to illustrate aspects of the Integral Method and practical aspects relevant to resolving near surface stress profiles using the fine-increment approach:

- Example 1: Selection of depth increments and numbers
- Example 2: Handling abrupt changes in stress
- Example 3: Effect of material non-linearity
- Example 4: Comparison of different analysis approaches
- Example 5: Conventional vs fine-increment drilling
- Example 6: Effect of strain smoothing

Example 1: Selection of depth increment and numbers

The choice and selection of drilling increments was discussed previously in Section 5.9, but to further demonstrate the requirement for increasing the size of the calculation increments at greater hole depths, two cases can be considered with different stress distributions and measurements carried out using a series of constant depth increments. Figure 12 shows the calculated cumulative relaxed strains for two steel specimen models; for each specimen, a 2 mm diameter hole and a series of constant depth increment of 128 μm have been used. In Case A, the residual stress field is of the equal biaxial type where $\sigma_1 = \sigma_3 = -100$ MPa. Case B is for a pure shear stress where $\sigma_1 = -\sigma_3 = -100$ MPa; the strain values plotted are those from element 1. The values of relaxed strains for uniformly distributed stresses are presented in Table 4 simply scaled from the triangular matrices of $\bar{a}$ and $\bar{b}$ coefficients. The plotted strains show how the case B strains are greater than those for case A and that there is a clear reduction of gradient with depth, particularly for the equal biaxial stress field (case A).

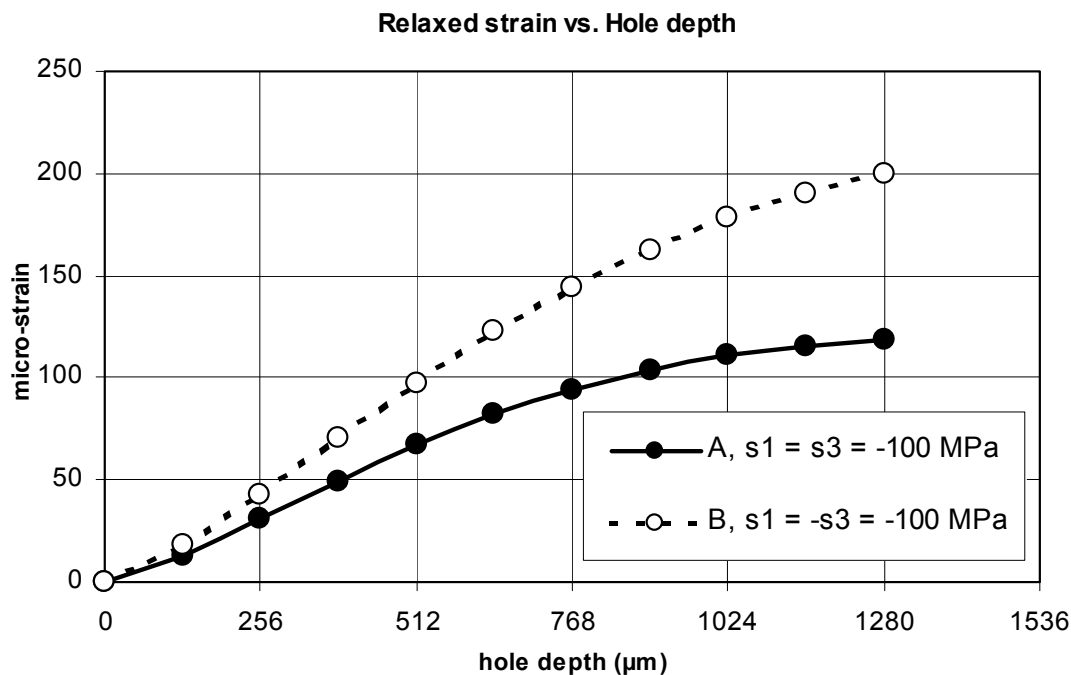


Figure 12: Cumulative strain: Steel material; 2mm diameter hole, 062RE target gauge

For the equal biaxial case (Case A), a strain of 12.9 $\mu\epsilon$ was relieved during the first drilling increment of 128 μm . During drilling of the final 128 μm increment (from depth 1152 μm to depth 1280 μm), the corresponding strain relief was calculated to change from 115.4 $\mu\epsilon$ to 118.5 $\mu\epsilon$. The tabulated values show that the 3.1 $\mu\epsilon$ strain difference from this final drilled increment comprises 2.7 $\mu\epsilon$ from deformation of the strain sensor caused by further relaxation of material previously drilled over the depth range 0 to 1152 μm and only 0.4 $\mu\epsilon$ from the relaxation of stresses within the final increment.

A, $s_1 = s_3 = -100$ MPa (equal biaxial stress)											
hole depth (microns)		stress depth (microns)									
	0	128	256	384	512	640	768	896	1024	1152	1280
	128	12.9									
	256	17.5	30.8								
	384	20.6	37.7	49.6							
	512	22.8	42.2	57.4	67.2						
	640	24.3	45.2	62.1	74.6	82.3					
	768	25.4	47.4	65.4	79.2	89.0	94.4				
	896	26.1	48.8	67.5	82.2	92.9	100.0	103.7			
	1024	26.6	49.8	69.0	84.1	95.4	103.3	108.3	110.6		
	1152	27.0	50.5	70.0	85.5	97.1	105.4	110.9	114.2	115.4	
	1280	27.2	50.9	70.6	86.3	98.1	106.7	112.5	116.2	118.1	118.5

Table 4a: Calculated strain readings for the uniform equal biaxial stress case

B, $s_1 = -s_3 = -100$ MPa (pure shear stress)											
hole depth (microns)		stress depth (microns)									
	0	128	256	384	512	640	768	896	1024	1152	1280
	128	18.1									
	256	23.4	42.9								
	384	27.1	51.6	70.3							
	512	30.0	57.4	80.6	97.5						
	640	31.9	61.5	87.1	107.9	122.4					
	768	33.3	64.4	91.5	114.3	132.1	144.3				
	896	34.3	66.4	94.8	118.7	138.0	152.8	162.8			
	1024	34.9	67.7	96.8	121.6	141.8	157.9	170.0	178.0		
	1152	35.3	68.6	98.2	123.5	144.4	161.2	174.2	184.0	190.4	
	1280	35.6	69.2	99.1	124.8	146.1	163.3	176.9	187.4	195.2	200.3

Table 4b: Calculated strain readings for the uniform pure shear stress state

This is a result of reduced strain sensitivity at the greater depths, and applies to all cases, irrespective of the initial stress distribution present. Recommendations presented in the previous section for 062 size gauges, suggest a total of 5 calculation increments for the “conventional” increment approach, 2 x 128 μm , 2 x 256 μm and 1 x 512 μm . For measuring near surface stresses with the “fine-increment” approach, the combination could be: 4 x 32 μm , 4 x 64 μm and 8 x 128 μm to the same final depth.

The number of increments chosen during fine-increment drilling has an impact on the time taken to complete the measurement and can have an important effect on the shape and resolution of the residual stress profile, particularly near to the surface. Figure 13 below shows data on a machined aluminium sample that has been measured using 20 μm increments and subsequently reanalysed using the same data, but at different increment steps. Some smoothing has been applied to the strain data.

Although the shape of the residual stress profile is similar in the three cases, there is variation in the fine detail. Both the 20 μm and 40 μm increment variants show better definition near the surface, but oscillations deeper, probably caused by the reduced sensitivity and small changes in strain readings between successive increments that contribute to the uncertainty and instability of the Integral method analysis (see Section 6.2). The example illustrates that consideration and planning should be made regarding the number and size of increments that should be used and, because of the reduced strain sensitivity at deeper depths; larger increments should be used away from the surface.

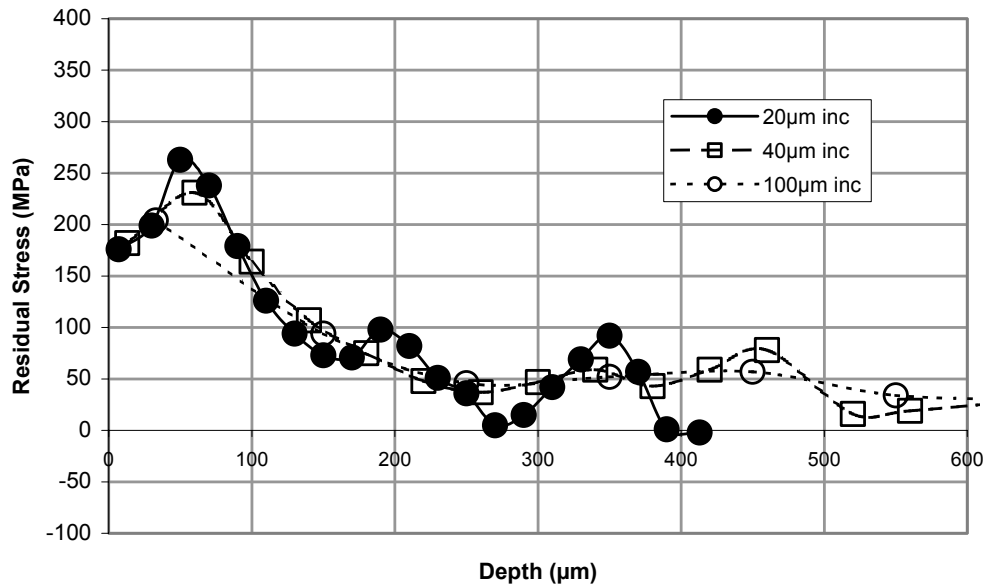


Figure 13: Example showing the effect of different numbers of increments on the calculated stress profile

Example 2: Abrupt change in stress

Where abrupt changes in residual stress distributions occur towards the full hole depth, the effect on the relaxed strain distributions are often difficult to detect. Figure 14 shows the calculated cumulative relaxed strains for two steel specimen models. As for the previous example, a 2 mm hole has been modelled in each specimen. In case A, the residual stress distribution is an equal biaxial stress field of -100 MPa. For case B in this example, the -100 MPa biaxial field extends only to a depth of 768 μm ; thereafter, the stress is zero. The two stress distributions are shown in the upper part of Figure 14.

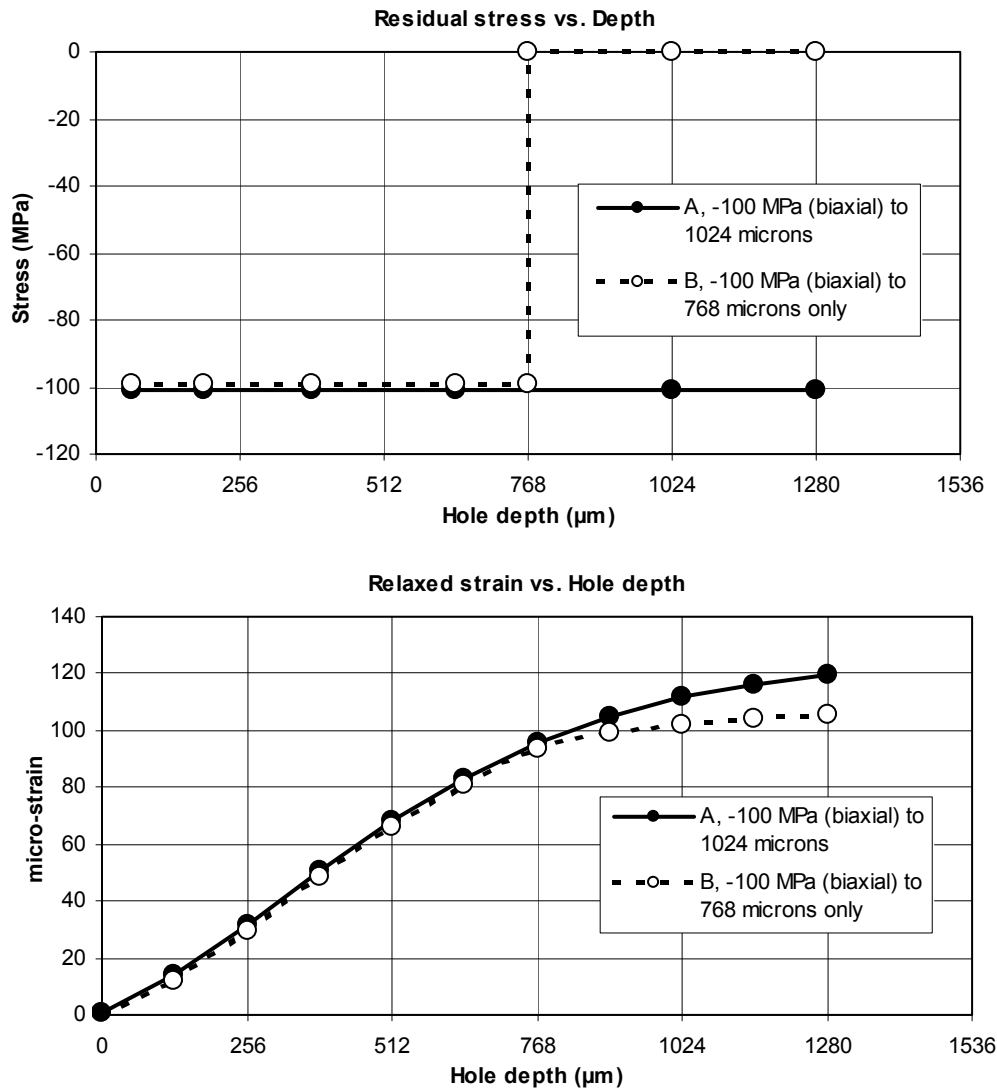


Figure 14: Cumulative strain in steel; 2 mm diameter hole, 062RE target gauge

The table below shows how, during the drilling of the 10 x 128 μm increments, the relaxed strains lie along the diagonal as shown by the arrow A. For case B, where there is a distinct change in the stress profile the strains lie along the diagonal of the table to a depth of 768 μm , but thereafter the increase in depth is accompanied only by strains associated with the further relaxation of stresses in the 0 to 768 μm depth range. The plotted relaxed strains in the lower part of Figure 14 confirm that the differences in distributions between the two cases appear to be relatively small in comparison to the differences in stress distributions. Indeed, the difference in final strains between A and B is smaller than the strain in the first increment.

When calculating residual stresses from relaxed strains using the Integral Method, the conditioning of equations resulting from the variation in sensitivity requires a very high standard of experimental strain data.

A, -100 MPa (biaxial) to 1024 microns							B, -100 MPa (biaxial) to 768 microns only				
hole depth (microns)	stress depth (microns)										
	0	128	256	384	512	640	768	896	1024	1152	1280
	128	12.9									
	256	17.5	30.8								
	384	20.6	37.7	49.6							
	512	22.8	42.2	57.4	67.2						
	640	24.3	45.2	62.1	74.6	82.3					
	768	25.4	47.4	65.4	79.2	89.0	94.4				
	896	26.1	48.8	67.5	82.2	92.9	101.0	103.7			
	1024	26.6	49.8	69.0	84.1	95.4	104.3	108.3	110.6		
	1152	27.0	50.5	70.0	85.5	97.1	106.4	110.9	114.2	115.4	
	1280	27.2	50.9	70.6	86.3	98.1	106.7	112.5	116.2	118.1	118.5

B

A

Table 5: Calculated strain readings for the 2 stress states modelled

Example 3: Effect of material non-linearity

In this example, a steel ring containing a circumferential weld has been machined and a number of target strain gauges applied and drilled. Results from a typical gauge close to the weld are shown in Figure 15; results are expressed as percentages of the material yield strength. In the case of the hoop stress results, near-surface stress magnitudes (depth <0.1 mm) have been influenced by the machining process, but the level of stress is seen to increase with depth. At depths greater than 0.1mm, however, it may be seen that the calculated hoop stress is significantly greater than the material yield strength (and may exceed the tensile strength).

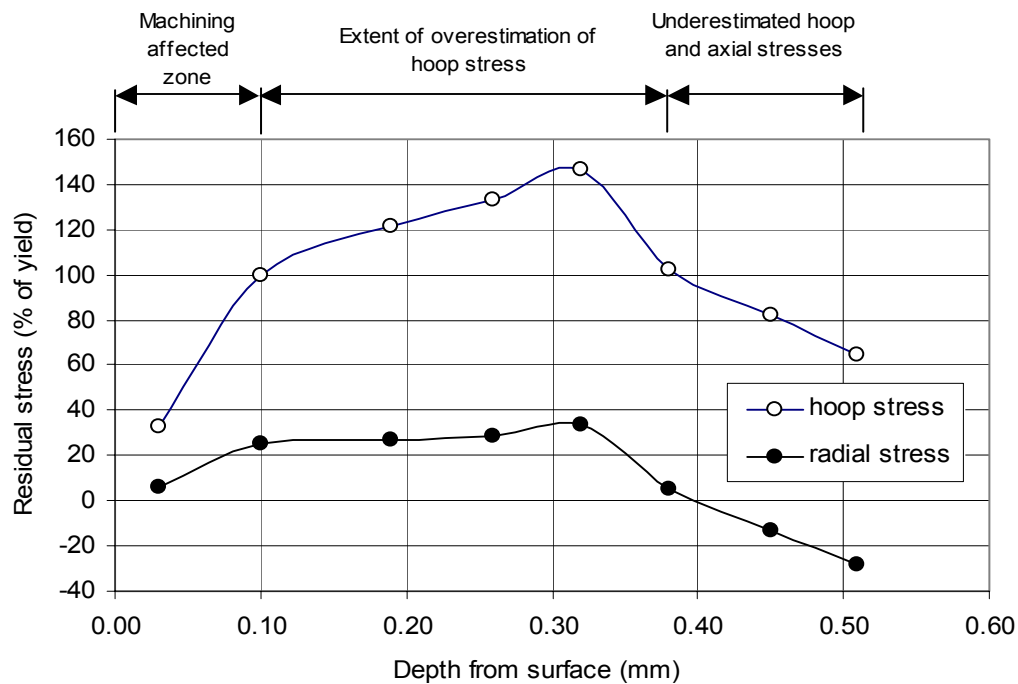


Figure 15: Effect of yielding on Integral method residual stress

While the sense of loading on the component indicated the presence of large tensile hoop stresses and much smaller axial stresses, the tensile stress magnitudes resulting from the Integral Method appear excessive. The following features are to be considered:

- The Integral Method used to calculate residual stresses from relaxed strains is based on a series of linear elastic models.
- As noted in Sections 4 and 5, where the residual stress approaches the material yield strength, the stress concentrating effect of the drilled hole causes non-linear behaviour of material immediately adjacent to the hole. Thus, changes in the stresses immediately adjacent to the hole are not linearly related to the strain measurements.
- In practice, when a stratum of material is drilled in which the residual stress approaches the yield stress, the residual stresses calculated from relaxed strains give an **overestimation** of the actual stresses within that stratum.
- At some point, during the drilling of subsequent strata at deeper hole depths, the contribution to surface strains from the previously drilled strata of ‘near-yield’ material will not be as large as predicted in the linear elastic model. The practical effect of this is that residual stresses calculated from the relaxed strains are an **underestimation** of the stress within the subsequent strata. In the example shown in Figure 15, this reversal is seen to occur around depth 0.32 mm. In more severe case, the underestimation may lead to a reversal in sign of the calculated stress.
- In the above example, the effects of yielding are not confined to the more tensile hoop stress. The results for the smaller axial stress also show a marked change in slope over the depth range 0.38 mm to 0.64 mm.

Clearly, the Integral Method based on linear elastic models cannot provide a satisfactory quantitative solution where near-yield stresses occur over significant depths. However, a careful inspection of calculated residual stress magnitudes (with reference to the material yield strength) can provide a limited qualitative result indicating the presence of ‘near-yield’ stress and its direction.

Example 4: Comparison of different analysis approaches

To examine the effect of the different analysis techniques available it is useful to analyse the same set of strain data using the different approaches. Two different stress profiles are considered below, and in both cases the data has been analysed using the *Uniform Stress*, *Power Series* and *Integral Method* approaches.

Because of the difficulty in generating a sample with a known uniform residual stress field, that will not be affected by superimposed stresses from machining or surface preparation, in the first example (below), calculated values for a uniform equal biaxial stress state, (the central plug in a “ring and plug” interference fit component), where there is no variation with depth, have been used. Figure 16 shows the data analyses from the fine-increment data presented earlier in Table 4a. Two different implementations of the Integral Method are also plotted for comparison, with different levels of smoothing.

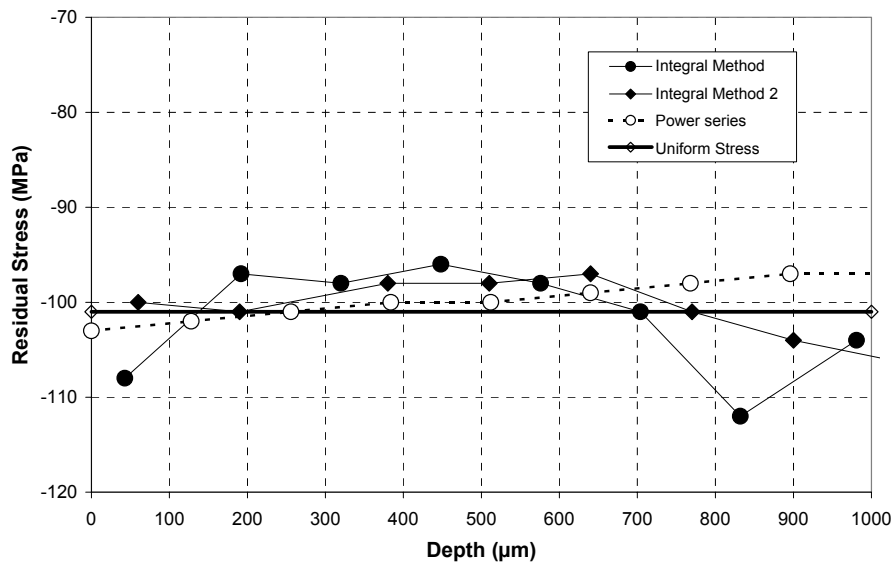


Figure 16: Stress profiles on a component with a uniform biaxial stress field calculated using the different analyses

Results show that all three analysis methods in this case give good results, although the profiles calculated according to the Integral Method show some variability and deviation from the true profile, particularly at the deeper increments, where the strain relief is smallest. Even then, for this case the variation is only 10% of the calculated value. The Power Series approach gives a reasonable approximation to the stress profile in this case.

Figure 17 shows the analysis of the residual stress profiles calculated from measurements made on a shot peened aluminium sample, where the stress varies with depth, calculated once again using the Uniform Stress, Power Series and Integral Method approaches.

In this case, there are clear and very obvious differences in the stress profiles calculated using the different approaches. Only the Integral Method gives the expected profile for a shot peened sample, where the peak compressive stress typically occurs at $\sim 100\mu\text{m}$ subsurface, returning to zero or a balancing stress at depths of 0.2-0.5mm, depending on the shot peening parameters. The Uniform Stress method gives a constant value of -95 MPa, which is clearly in error; the Power series gives some indication of the variation with depth, but does not resolve the subsurface peak, and the predicted near surface measurement is very different to that predicted by the Integral method.

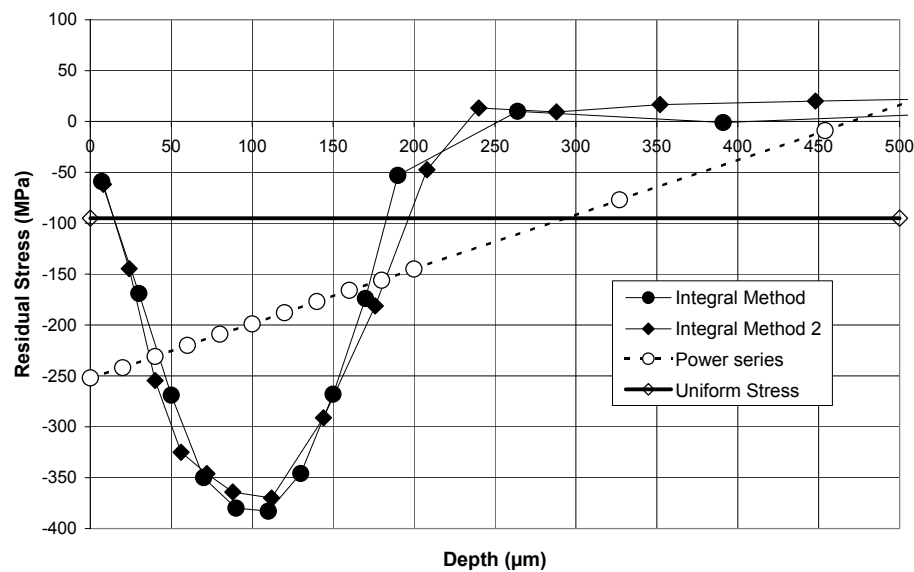


Figure 17: Stress profiles on a shot peened aluminium specimen calculated using the different analyses

Due to reservations and restrictions with some of the other analysis approaches, as mentioned in previous sections of the Guide, the Integral Method is recommended as the preferred analysis method for measuring the variation of residual stress with depth.

Example 5: Conventional vs fine increment drilling

In this example [32], a nickel alloy disc has been subjected to high speed machining (turning) to achieve a high rate of material removal, and measurements carried out using the fine-increment approach to characterise the resultant near-surface residual stress profile. Results are compared with data analysed using the conventional 128 μm increments. The fine increment hole drilling was carried out close to the outer diameter using increments of 6 x 16 μm , 5 x 32 μm , 6 x 64 μm and finally 2 x 128 μm to give a completed hole depth of 0.9 mm. The residual stress distribution calculated using the fine-increment data confirms the presence of tensile circumferential and radial stress maxima within the first drilled increment. The highly detailed distributions in Figure 18 show how these stresses decay rapidly away from the surface. However, the compressive ‘bulk’ circumferential and radial stresses within the disc structure (resulting from previous heat treatment) are approximately -300 MPa and -100 MPa, respectively, at the gauge shown here. Accordingly, when the relaxed strain data is processed at ‘coarse’ 128 μm depth increments, circumferential and radial stresses are calculated as compressive at all depths. While the near-surface gradient of circumferential stress from the coarse data does show a reduction in compression, the averaging effect of the larger calculation increment masks the severity of gradients and the stress maximum in excess of 400 MPa revealed by the fine-increment calculation.

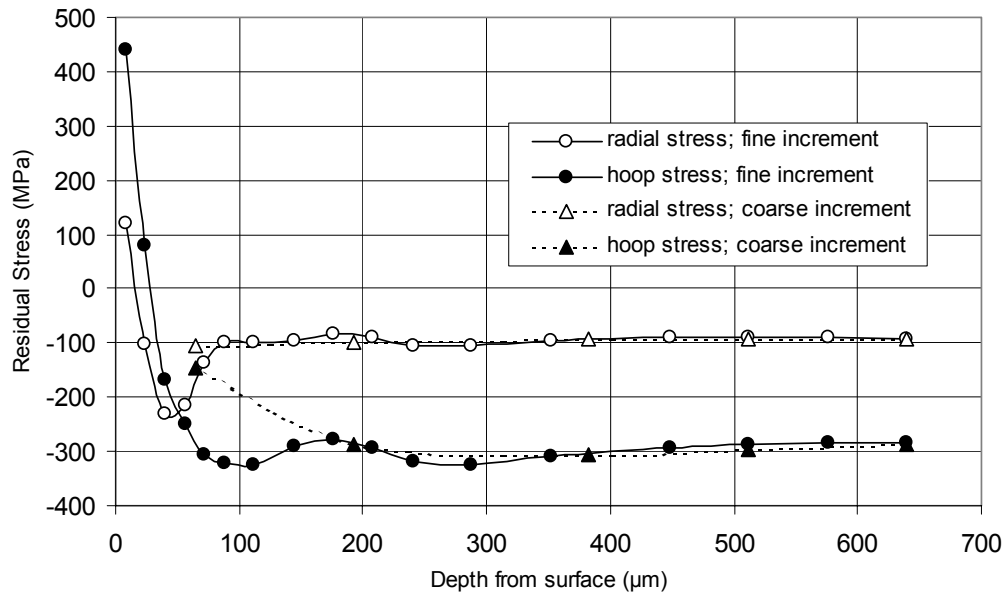


Figure 18: Near surface detail from fine increment drilling [32]

One important aspect of reducing the size of calculation increments is the effect of strain measurement uncertainties on the calculated stress values. In the example given above, the sensitivity of average stresses in the first 16 μm increment is approaching $-90 \text{ MPa}/\mu\epsilon$. The resolution of many strain indicators is $1\mu\epsilon$. By increasing the first calculation increment to 32 μm the sensitivity is changed to approximately $-50 \text{ MPa}/\mu\epsilon$ - that is, a twofold increase in relaxed strain for a given stress. However, the increase in increment size also results in a loss of detail in the calculated stress distribution. One method of retaining near-surface detail that can be applied while increasing the effective strain output is to increase the diameter of the drilled hole. However, in extreme cases of hole diameters (when D/D_0 approaches 0.5) the edge of the drilled hole is located close to the innermost edges of the gauge element. This proximity can lead to severe local shearing at the gauge/component interface and premature failure of the bond because of additional thermal and mechanical loading during the drilling process.

Example 6: Effect of strain smoothing

The data presented in Example 4 above was analysed using two different implementations of the Integral method, and there are small and subtle differences between them. A factor that contributes to this is the level of smoothing. Figure 19 shows the residual stress profiles calculated from the same starting strain values with different levels of smoothing.

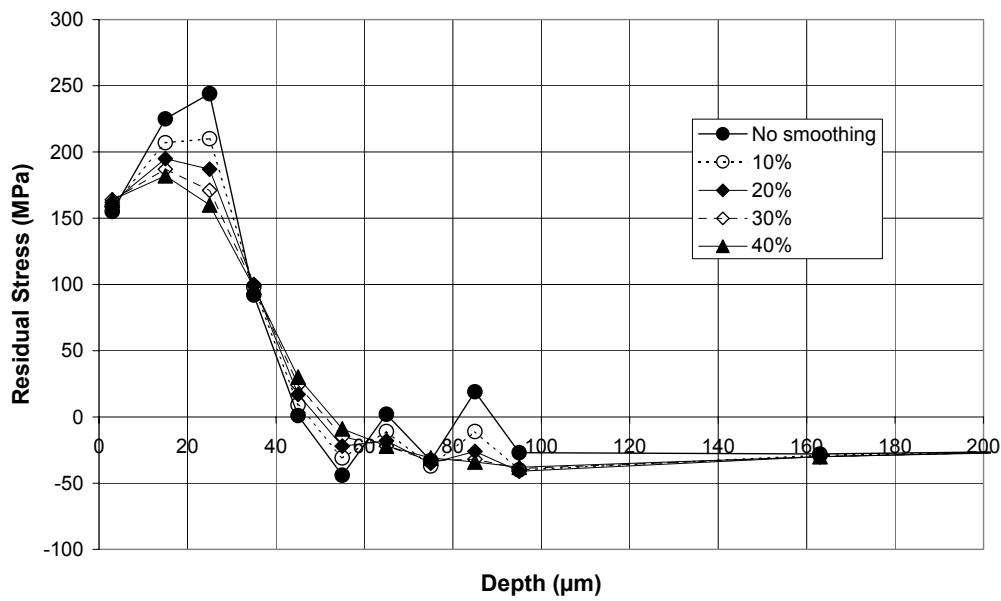


Figure 19: Effect of different levels of smoothing on the calculated stress profiles (Integral method)

Where possible the effect of smoothing should be examined on the calculated stress profile and can be included as a factor in the uncertainty budget for the measurement. In the above example different levels of smoothing have been applied, with the effect of reducing the oscillations and spikes in the residual stress profile, but with an important influence on the peak residual stress value measured, which varies from ~250 MPa to ~175 MPa depending on the level of smoothing.

Users are encouraged to examine this effect with their own measurements and analysis software, and where possible validate the stress profile with comparative measurements made using other techniques. A standard measurement procedure, increment selection and data analysis should then be used for all subsequent measurements.

6.4 Conclusion

Versions of the Integral Method software are available from commercial sources (Vishay Measurements Group, HBM, Stresscraft etc). However, operator skill and vigilance remains an essential part in the successful application of the Integral Method. In particular :

- The selection of drill depth increments and calculation increments can be developed to provide reasonable stress distribution detail whilst maintaining acceptable levels of uncertainty.
- Distributions of relaxed strains can be examined to detect any systematic problems with the drilling equipment, strain gauge rosette or strain sensor.
- Any concerns arising from the final condition of drills (damage or wear) or hole shape (diameter, depth, eccentricity, circularity, etc) can be reviewed in conjunction with the relaxed strain distributions. Thus, analysis of strain data should remain ‘close’ to the drilling / strain measurement process.

In addition to residual stress calculations, the selected software must also provide the means for :

- The presentation of strain and stress data for reporting purposes. This includes tabulated strains for each drilling depth increment, direct and shear stresses (in the directions of the rosette gauges) and principal stresses. Plotted distributions of stresses (gauge direction or principal stresses) will also form an important part of this presentation along with an indication of the directions of principal stresses at some reference depth(s).
- The combination of results from several gauges to provide a results summary (or export to a spread sheet for this purpose and for data transmission).
- The storage of specimen/subject details and gauge, strain and hole dimension data in an orderly catalogue for retrieval and archiving.

An example of a typical output from a residual stress software package is shown in Figure 20 below.

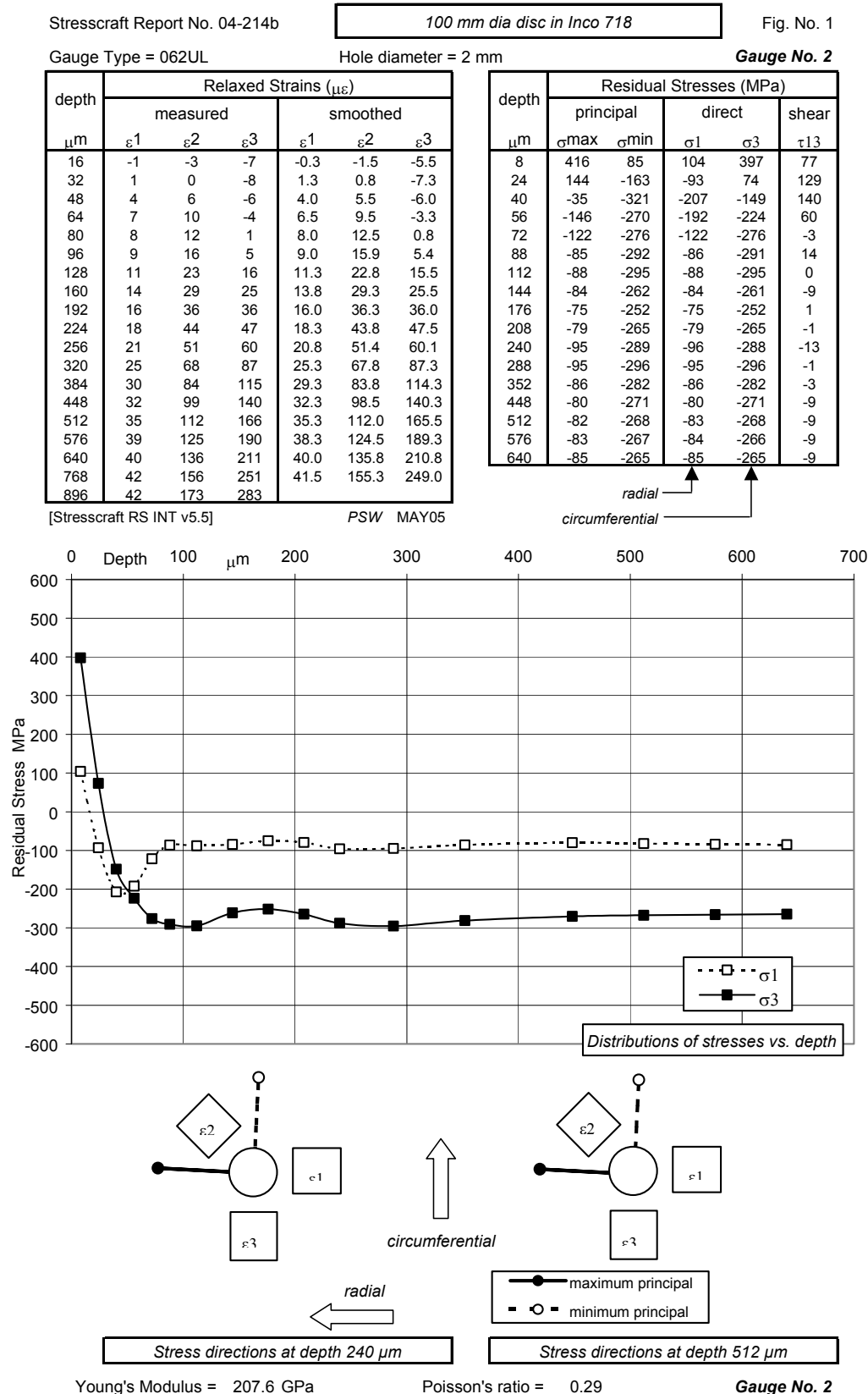


Figure 20: Graphical presentation of measured strain and calculated residual stress data (courtesy of Stresscraft)

7 Non-contact strain measurement methods

The conventional hole drilling approach is relatively quick and straightforward, but there are some disadvantages with using strain gauges. In particular, the strain gauge approach requires thorough surface preparation, only permits a restricted range of hole sizes commensurate with the specific gauge design, should be carried out with accurate alignment and drilling, and only provides limited data averaged over the footprint of the strain gauge grid.

There is significant interest therefore in using an approach that replaces the conventional strain gauge with a full field non-contact strain measurement, where the residual stresses are determined from the strains (or displacements) that develop as a result of drilling the hole. Developments in recent years [33-53] have already led to the application of grating interferometry (Moiré), electronic speckle pattern interferometry (ESPI) and laser holography in place of the strain gauge during the hole drilling process.

The techniques that use Moiré or grating interferometry offer significantly increased resolution and sensitivity compared with the strain gauge, but still require some degree of surface preparation, as a diffraction grating must be bonded to the component; they are generally not as robust as an encapsulated strain gauge and therefore must be handled carefully. Considerable development has been carried out by Wu, Lu and co-workers on a variety of components with different residual stress states and the reader is referred to Refs 34-36 for more detailed background on the technique.

The technique works by using a grating on the sample and a second virtual reference grating, which is imaged on the specimen grating using an optical system based on two-beam interference. Drilling is generally carried out in discrete steps with the drill head removed from the component and replaced by a camera to capture the image at each step. Because the reference grating does not change during the hole drilling process, the interaction between the two gratings produces fringes that represent the local in-plane displacement of the specimen. A number of steps must be carried out to process the data, including fringe counting and the calculation of the fringe gradient to determine the sign of the stresses. In the past this has been a manual process, but more powerful computers have led to the development of unwrapping and differentiating techniques to generate full field strain maps from the images. Based on a grating with 1200 lines/mm the displacement sensitivity is $0.417 \mu\text{m}/\text{fringe}$, but recent analyses based on phase stepping and automated processing can realise an order of magnitude improvement. Figure 21 shows some of the stages and typical results from measurements carried out from a full depth hole in a shot peened aluminium sample [53].

Other non-contact methods that have been developed for use with hole drilling include electronic speckle pattern interferometry (ESPI) and digital holographic techniques. These methods have the advantage over grating interferometry in that they generally do not require special surface preparation (diffusely reflective surface), but they are still sensitive to vibrations and to some extent this limits their application to a laboratory environment.

Much of the early development work in using holography with hole drilling was carried out in the mid-1980s [38,39]. Initial work focused on developing the analysis for residual stress fields that were uniform with depth, but this has been extended by various workers [40-48] to components with more complicated stress gradients, biaxial stress states and incremental drilling, including the novel approach of using variable diameter holes.

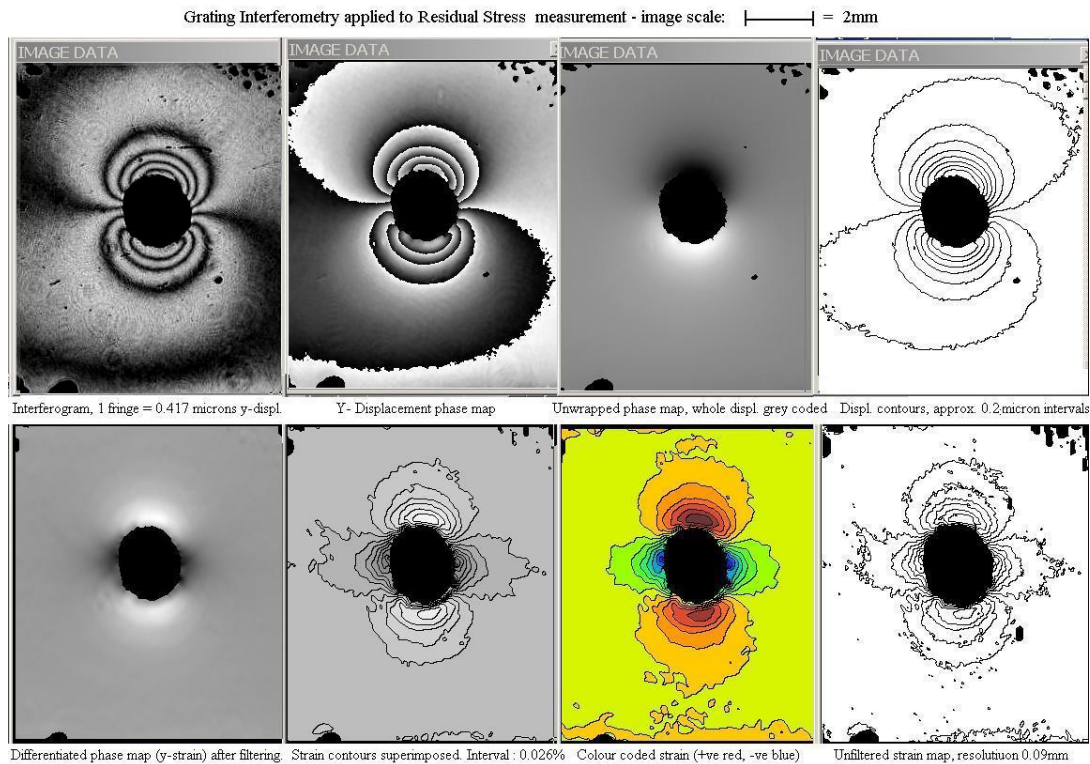


Figure 21: Typical fringe patterns and process steps during hole drilling using grating interferometry [53]

The early studies relied on the use of holographic plates to capture the fringe patterns and manual fringe counting, but with the development of ESPI techniques and digital technology the speckles are sufficiently large to be resolved by conventional CCD cameras, and much of the data processing can now be carried out automatically. The Hytec PRISM system, developed by Steingig et al [50-52] is probably the first commercially available system, combining hole drilling with full field non-contact strain measurement.

It is clear that hole drilling systems based on full field non-contact strain measurement offer many advantages over the conventional strain gauge approach including the potential for rapid measurements with limited surface preparation, the ability to extract additional data from the strain field around the hole, and the relative simplicity of the approach. Although the non-contact full field strain approach is attractive to a wide range of industries and applications, the current limitations with the methods are the high cost compared with using strain gauges, their sensitivity to vibration and limited portability.

Whilst these have shown success and been able to resolve more information from the hole-drilling test, generally they are expensive solutions that require setting up on an optical bench and not practical approaches that can be readily used outside the laboratory.

8 Uncertainty analysis

It is good practice in any measurement to quote the uncertainties associated with the measurement itself, but this is rarely considered in hole drilling investigations. Some practitioners of the hole drilling technique believe the method to be more qualitative than quantitative, especially when the conditions in the component under test fall outside the scope of the ASTM standard and Measurements Group Technical Note. It is possible however to make some estimate of the uncertainties associated with the test method, and this is a valuable approach which should be encouraged as it can help to identify which experimental parameters or aspects of the test are likely to give rise to the greatest uncertainty. If used properly it can help to refine the experimental set up.

A Code of Practice (CoP) for determining the uncertainties associated with the hole drilling technique was produced as part of the UNCERT project (EU Standards Measurement & Testing Project No. SMT4-CT97-2165). In this project a series of documents were produced, in a common format, for determining the uncertainties in a variety of mechanical tests on metallic materials. CoP 15 [54], which deals with the hole drilling technique, was one of 17 produced by the UNCERT consortium. The document contains a standard procedure for estimating uncertainties, together with some background to the technique and a worked example. The basic procedure can be broken down into a number of steps:

- Step 1: Identify the parameters for which the uncertainty is to be estimated
- Step 2: Identify all sources of uncertainty in the test
- Step 3: Classify the type of uncertainties
- Step 4: Estimate the sensitivity coefficient and standard uncertainty for each major source
- Step 5: Compute the combined uncertainty
- Step 6: Compute the Expanded uncertainty
- Step 7: Reporting of results

The table on the following pages include a list of parameters that have been identified in CoP15 as having an influence on the uncertainty in the residual stress measurement. The list is not exhaustive, but it is an excellent starting point, and it is recommended that each laboratory individually consider their own particular experimental set-up and data analysis procedures to identify which parameters are likely to have the greatest effect on the quality of their measurements.

This exercise was carried out within a group of UK experts and the results are summarised in the table. Although there was some disagreement regarding some of the markings it is clear that several key sources of uncertainty have been identified. Amongst the most important are the initial surface condition, identification of the zero reference depth and subsequent depths for incremental drilling, the data reduction and analysis techniques used. **The operator skill has been identified as probably the most important parameter in achieving a reliable and quality measurement.**

Source of Uncertainty	Likely Contribution	Comments
1. Component (or test sample)		
1.1 Material	2	Generally small
1.2 Surface condition (Surface texture, roughness, evenness, flatness, oxidation)	1	For first 2 increments – 2 thereafter
1.3 Material properties E , μ & σ_v	2	Small cf other data
1.4 Isotropy	2	
1.5 Homogeneity, porosity, inclusions, etc.	2	
1.6 Access to measurement location		
1.7 Stress gradient (σ_z , σ_{xz} , σ_{yz})	1	If improper data analysis used
1.8 Constraints (i.e. measurement is located near an edge, a hole, or near a stress-concentration)	2	
1.9 Geometry (including thickness)	2	If thin or curved
2. Measuring Instrument		
2.1 Drill feed		Usually pre-set
2.2 Drill speed		Pre-set
2.3 Drill diameter		Hole diameter (3.5) more important
2.4 Drill wear	2	Should be monitored
2.5 Eccentricity (With respect to machine axis)	2	Pre-set
2.6 Concentricity (With respect to the centre of gauges)	2	Optical alignment
2.7 Accuracy of depth measurement	1	See 1.2 - Important for incremental drilling
2.8 Rigidity of drilling rig		
2.9 Number of strain gauges		Spacing > 8 diameters
2.10 Rosette diameter		
2.11 Tolerance of gauge positioning		Only significant if 1.7 is high
2.12 Gauge factor		Use tabulated values
2.13 Gauge alignment		Use skilled operator
2.14 Target positioning		
2.15 Quality of gauges (Including gauge supplier, number of wires, temperature-compensation)	2	Use controlled supplier
2.16 Quality of installation (Including surface preparation, gauge bonding, adhesive type, wiring)	2	Use skilled operator
2.17 Resolution of read out instrument	1-2	
2.18 Accuracy of read out instrument		Calibrate
2.19 Linearity of read out instrument		
2.20 Excitation voltage		

* [1 = Major contribution, 2 = minor contribution, blank = insignificant (or no) contribution]

Table 6: Some experimental parameters that may affect the uncertainty in the hole drilling measurement. Contributions identified by UK Hole Drilling Focus Group.

Source of Uncertainty	Likely Contribution *	Comments
3. Measurement Procedure		
3.1 Definition of zero reference	1	See 1.2
3.2 Strain gauges errors (Drift or non-zeroing)	2	
3.3 Value of increment step		Usually preset
3.4 Hole depth		See 1.2
3.5 Hole diameter	2	Usually well controlled
3.6 Hole perpendicularity		Importance depends on hole depth
3.7 Hole roundness (& tapering of the hole and corner radius)	2	
3.8 Breakage of tool		Not permitted – repeat measurement
3.9 Temperature rise	2	Effect sometimes observed
3.10 Time interval before taking a reading		Allow to stabilise
3.11 Data reduction technique	1	EUS invalid for most work
3.12 Method of calculations	1	
4. Operator		
4.1 Operator skill	1	The most important factor
5. Environment		
5.1 Ambient temperature		
5.2 Ambient humidity		

* [1 = Major contribution, 2 = minor contribution, blank = insignificant (or no) contribution]

Table 6 (cont): Some experimental parameters that may affect the uncertainty in the hole drilling measurement. Contributions identified by UK Hole Drilling Focus Group.

Once the major sources of uncertainty have been identified they must be classified according to type, and some estimate made of their effect on the overall uncertainty of the parameter (strain readings or residual stress values in this case) being investigated. This may involve a sensitivity analysis or direct calculation of the effect. Further details, together with a worked example are given in [54].

The combined uncertainty is then calculated by the root sum squares approach, from which the expanded uncertainty can be determined. This is obtained by multiplying by a coverage factor, k , which is selected on the basis of the confidence level required. For a normal probability distribution, a coverage factor, $k=2$, corresponds to a confidence interval of 95%. The result should then be reported as the mean value $\pm$ expanded uncertainty.

The main purpose of developing an uncertainty budget is to identify which parameters have the greatest effect on the quality and scatter in the measurement and to provide the author

with a degree of confidence in the quality and accuracy of the result. All users are recommended to give this consideration and identify their own uncertainty budget for the hole drilling measurement.

9 Reporting of results

The reporting of the results will depend on the requirements of each organisation and the individual customer but the following parameters are recommended for inclusion in the test report:

- A sketch, photograph or note of the measurement location and direction of the strain gauge rosette
- Reference to appropriate test procedure (in-house, ASTM E837 or MG TN-503-5)
- Date of test
- Name of operator
- Material parameters used in the calculation (whether handbook data or from a separate test)
- Strain gauge type, size, gauge factor, temperature compensation
- Details of surface preparation and adhesive type used
- Details of the strain gauge instrumentation – with reference to relevant calibration certificates if possible
- Temperature and environmental conditions if appropriate
- Details of the drilling equipment
- Drill type and diameter
- Number and depth of each increment
- Diameter of the final hole
- Depth of final hole (cross referenced to micrometer setting)
- Table of raw strain data from each gauge at each depth increment
- Any corrections or smoothing applied to the strain data (eg to take into account drift or systematic experimental error)
- Data reduction and analysis techniques used
- Details of software used – type, version etc.
- Distribution of stresses calculated over the entire drilling range
- Plot of strain data vs normalised depth to check for stress uniformity
- Full depth maximum and minimum residual stress values
- Details of uncertainty budget and calculations
- Comments on results or the test itself where appropriate

10 Summary of observations and recommendations

A number of observations and recommendations to improve the accuracy of the hole drilling measurements have been made throughout this Guide. **Operator skill has been identified as probably the most important factor in achieving a reliable and quality measurement.** Some of the main recommendations are summarised below:

SURFACE PREPARATION

Surface preparation and installation procedures need to be of the highest quality. This is particularly important in incremental hole drilling as the strains measured are generally quite small (typically only several $\mu\epsilon$ in the first depth increment), and considerably lower than those measured in a conventional mechanical test at the same stress level.

If near-surface measurements are required then it is likely that the abrasion technique will influence the accuracy of the first increment measurement. Beyond the first increment, however, the degree of abrasion is less likely to influence the results.

For many materials, mechanical methods of surface preparation can be avoided by the use of a localised etching process; the finish is usually matt in appearance and capable of providing an effective anchor for the strain gauge bond.

GAUGE SELECTION AND INSTALLATION

The user is recommended to purchase good quality gauges (for which the calibration coefficients are readily available) from a reliable supplier, and use recommended strain gauge installation procedures as the stress values measured are strongly affected by the quality of the installation and expertise of the user.

The primary factor to be considered in gauge selection is size, because of the relationship between gauge size and the available target area, the integration area and depth information required. Smaller gauges use smaller holes and can be used for fine 'near-surface' measurements.

Experimentally generated errors associated in the measurements with small strain gauges (accuracy of hole drilling, control of depth etc.) are likely to be higher than the corresponding measurements with larger gauges. Large gauges still require careful handling because of the sizes of drills required and large amount of material to be removed.

Two simple checks are recommended to validate the integrity of the installation - if possible a small mechanical loading can be applied to the sample and the strain readings before and after loading noted; if the gauge installation is good there should be no hysteresis or difference in the gauge readings, and the strains should return to zero after the load is removed. It is also recommended that a visual inspection of the gauge installation be carried out, as areas that are not well bonded often show up. In such cases the gauge should be removed and the installation repeated.

DRILLING

The recommended drill suitable for most materials is the inverted cone tungsten carbide type. Diamond impregnated cutters do not cut a hole with a 'sharp' corner and the residual stress data from near-surface increments is to be treated with caution.

Abrasive jet machining is not recommended for the incremental hole drilling because of the poor hole geometry and control of depth. High-speed drilling is generally suitable for most materials.

It is essential that a new drill be used for each measurement. Drills should be subjected to a brief visual inspection (x3 eyepiece) prior to use and discarded after use in drilling one hole.

Orbital drilling should be considered, as it offers reduced cutting forces and more stable strain readings. It allows the use of smaller drills, and can be applied to harder materials using conventional tungsten carbide cutters.

The number and size of drilling increments should be planned before testing, and be chosen to reflect the purpose of the test and the nature of the residual stress profile. For general purposes between 8 and 14 increments may be sufficient to give the required detail, but with fine increment drilling, where the focus is in the near surface information, the user may proceed with a larger number of smaller near-surface increments.

ALIGNMENT

It is crucial that the user examines the experimental set up for possible errors as a result of off-axis alignment before each test.

ZERO DEPTH DETECTION.....

Accurate zero depth detection is vital to good quality measurements.

Particular care should be taken if the fine increment approach is being used as errors in the definition of the zero depth position can have a large influence on the calculated near surface residual stress profile.

Operators are encouraged to develop a procedure for accurate removal of the gauge backing and zero depth detection. Oblique observation of the drilling process through a mini-video camera, magnifying eyeglass, travelling microscope or telescope is recommended.

TEMPERATURE CONSIDERATIONS

In large components, in field installations, or where some local heat has been applied to achieve gauge bonding the effect of changes in component temperature should be considered.

For inspection and illumination, a cold light source should be used as conventional light sources can introduce considerable thermally generated strains in the gauge leading to large errors and drift in the strain readings.

ANALYSIS TECHNIQUES

The **Integral Method** should be used as the **preferred method of data analysis**.

When calculating residual stresses from relaxed strains using the **Integral Method**, the conditioning of equations resulting from the variation in sensitivity requires a very high standard of experimental strain data.

The **Integral Method** is able to decode relaxed strains that relate to highly non-uniform residual stress distributions. Five or six calculation increments yield a satisfactory level of detail for most stress distributions, and the problem of reduced sensitivity with increasing hole depth is addressed by increasing the size of calculation increments at greater depths.

For cases where the stresses may be close to yield, careful inspection of the calculated residual stress magnitudes (with reference to the material yield strength) can provide a limited qualitative result indicating the presence of 'near-yield' stress and its direction.

Where possible the effect of strain smoothing should be examined on the calculated stress profile and can be included as a factor in the uncertainty budget for the measurement. Users are encouraged to examine this effect with their own measurements and analysis software, and where possible validate the stress profile with comparative measurements made using other techniques. A standard measurement procedure, increment selection and data analysis should then be used for all subsequent measurements.

ASTM E837-01 and Measurements Group TN-503-5 are not suitable for use with nonuniform stress fields. Both include checks for non-uniformity but the tests outlined are not a sensitive indicator of stress field uniformity, but rather a means of identifying extremely nonuniform stress fields.

The Equivalent Uniform Stress approach suggested in TN-503-5 is useful for comparison purposes, but has limited value for practical engineering applications, as it does not give a true value for the residual stresses present.

NON-CONTACT STRAIN MEASUREMENT

Hole drilling systems based on full field non-contact strain measurement offer many advantages over the conventional strain gauge approach including the potential for rapid measurements with limited surface preparation, the ability to extract additional data from the strain field around the hole, and the relative simplicity of the approach. Current limitations with the methods are the high cost compared with using strain gauges, their sensitivity to vibration and limited portability.

UNCERTAINTY

Operators are recommended to develop an uncertainty budget for their own experimental set-up, to investigate and identify the parameters are likely to give rise to the greatest uncertainty.

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Appendix 1 – Directory of UK Hole Drilling Experts and Contacts

As part of the knowledge transfer activity at NPL, a directory of UK hole drilling users and experts has been established. Brief details are given below and are also available in full on the NPL Residual Stress website at <http://www.npl.co.uk/materials/residualstress>

Airbus UK		Dr Richard Burguete
AWE		Andrew Johnson
Bristol University		Dr Chris Truman
Corus Group		Craig Middleton
HBM		Nick Gittins
Measurements Group UK		Anton Chitney
National Physical Laboratory		Dr Jerry Lord
The Open University		Dr Mike Fitzpatrick
Procter & Chester		Niall Pigott
Rolls-Royce		Andy Backler
Stresscraft		Dr Philip Whitehead
The Welding Institute		Dr Andy Ezeilo

Organisations appear in alphabetical order only. All contacts below have supplied basic information on their levels of expertise and available facilities, and have agreed to be listed here. All have described themselves as experts in the technique and have facilities or access to facilities for making appropriate measurements.

NPL takes no responsibility for the contents of this list; none of the experts, organisations, facilities or services listed here have been reviewed by NPL and the list is meant purely as a starting point for obtaining residual stress measurements and/or further information.

