

A Review of Residual Stress Measurement Methods - A Guide to Technique Selection

by

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SUMMARY

This review has been carried out as an activity in project CPM4.5, on the *Methods of Measuring Residual Stress in Components*, which is part of the CPM programme on *Characterisation and Performance of Materials*, funded by the Engineering Industries Directorate of the UK Department of Trade and Industry. It is the deliverable for Task 1.

The purpose of this review is to provide an overview of some of the recent advances in the area of residual stress measurement and act as a summary document to aid technique selection. The intention is not to duplicate what has already been published, because a number of comprehensive reviews of residual stress measurement methods are already available, but to provide advice and guidance on some of the issues associated with the measurement of residual stress.

The results of a UK industrial survey of current interests and expertise in residual stress measurement are presented, together with guidelines on technique selection and some advice on quantifying the measurement uncertainty and accuracy. The physical limitations of the various techniques currently used are also summarised.

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ISSN 1473-2734

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1 INTRODUCTION TO RESIDUAL STRESS

The key aim of this report is to provide an overview of some of the recent advances in the area of residual stress measurement and act as a summary document to aid technique selection. A number of comprehensive reviews of residual stress measurement methods have already been published in the literature [1-16] and the reader is directed to these for detailed information on the specific attributes of the various techniques.

The results of a UK industrial survey of current interests and expertise in residual stress measurement are presented in the report, together with guidelines on technique selection and some advice on quantifying the measurement uncertainty and accuracy. The physical limitations of the various techniques currently used are also summarised.

1 Definition

Residual stresses can be defined as those stresses that remain in a material or body after manufacture and processing in the absence of external forces or thermal gradients. Residual stress measurement techniques invariably measure strains rather than stresses, and the residual stresses are then deduced using the appropriate material parameters such as Young's modulus and Poisson's ratio. Often only a single stress value is quoted and the stresses are implicitly assumed to be constant within the measurement volume, both in the surface plane and through the depth.

Residual stresses can be defined as either macro or micro stresses and both may be present in a component at any one time. *Macro residual stresses*, which are often referred to as Type I residual stresses, vary within the body of the component over a range much larger than the grain size. *Micro residual stresses*, which result from differences within the microstructure of a material, can be classified as Type II or III. Type II residual stresses are micro residual stresses that operate at the grain-size level; Type III are generated at the atomic level.

Micro residual stresses often result from the presence of different phases or constituents in a material. They can change sign and/or magnitude over distances comparable to the grain size of the material under analysis.

To summarise, residual stresses can be classified as [1,10,14]:

Type I	which refer to macro residual stresses that develop in the body of a component on a scale larger than the grain size of the material.
Type II	are micro residual stresses that vary on the scale of an individual grain. Such stresses may be expected to exist in single-phase materials because of anisotropy in the behaviour of each grain. They may also develop in multi-phase materials because of the different properties of the different phases.
Type III	are micro residual stresses that exist within a grain, essentially as a result of the presence of dislocations and other crystalline defects. Types II and III are often grouped together as microstresses.

The different types of residual stress are shown schematically in Figure 1.

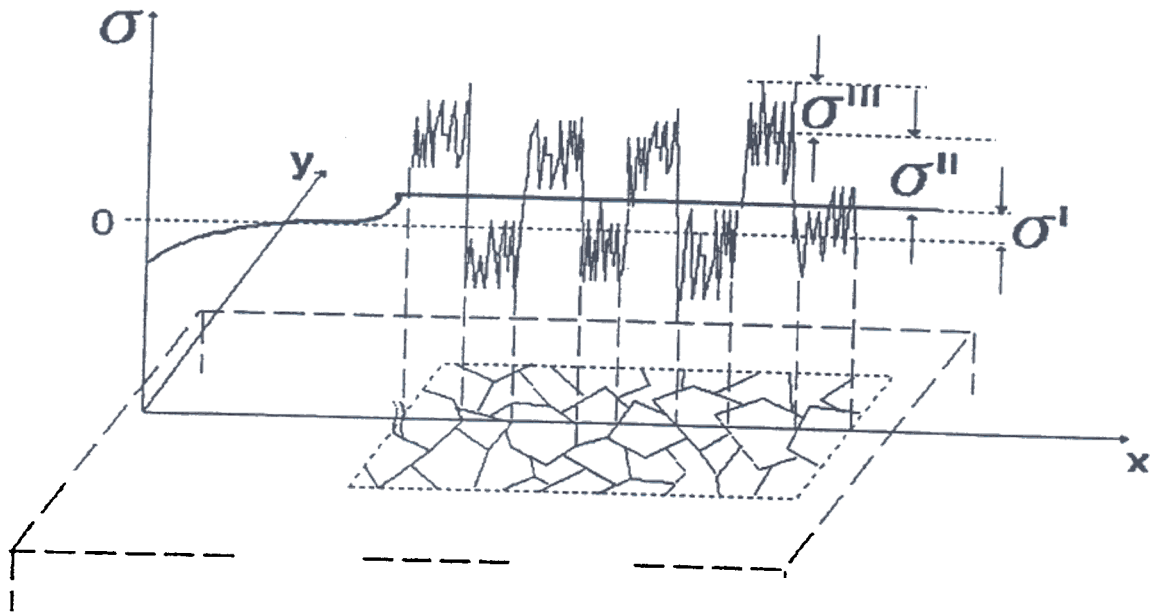


Fig.1 Categorisation of residual stresses according to length scales.

When comparing results from different techniques, consideration should be given to the sampling volume and resolution of each measurement method in relation to the type of residual stress being measured, particularly when the Type II and III micro residual stresses are of interest. It is important also to consider the concept of the characteristic volume, which can be used to describe the volume over which a given type of residual stress averages to zero. Most material removal techniques (e.g. hole drilling, layer removal) remove large volumes of material over which Type II and III stresses average to zero so that only the macro residual stresses can be measured.

1.2 Origins

Residual stresses develop during most manufacturing processes involving material deformation, heat treatment, machining or processing operations that transform the shape or change the properties of a material. They arise from a number of sources and can be present in the unprocessed raw material, introduced during manufacturing or can arise from in-service loading [2,9,10,14]. The residual stresses may be sufficiently large to cause local yielding and plastic deformation, both on a microscopic and macroscopic level, and can severely affect component performance. For this reason it is vital that some knowledge of the internal stress state can be deduced either from measurements or modelling predictions.

Both the magnitude and distribution of the residual stress can be critical to performance and should be considered in the design of a component. In any free standing body stress equilibrium must be maintained, which means that the presence of a tensile residual stress in the component will be balanced by a compressive stress elsewhere in the body. Tensile residual stresses in the surface of a component are generally undesirable since they can contribute to, and are often the major cause of, fatigue failure, quench cracking and stress-

corrosion cracking. Compressive residual stresses in the surface layers are usually beneficial since they increase both fatigue strength and resistance to stress-corrosion cracking, and increase the bending strength of brittle ceramics and glass. In general, residual stresses are beneficial when they operate in the plane of the applied load and are opposite in sense (for example, a compressive residual stress in a component subjected to an applied tensile load).

The origins of residual stresses in a component may be classified as:

- Mechanical
- Thermal
- Chemical

Mechanically generated residual stresses are often a result of manufacturing processes that produce non-uniform plastic deformation. They may develop naturally during processing or treatment, or may be introduced deliberately to develop a particular stress profile in a component [17]. Examples of operations that produce undesirable surface tensile stresses or residual stress gradients are rod or wire drawing (deep deformation), welding, machining (turning, milling) and grinding (normal or harsh conditions). Figure 2 shows characteristic residual stress profiles resulting from 3 different types of grinding [18]. It can be seen that conventional and highly abrasive grinding produced tensile stresses near the surface compared with compressive stresses with gentle grinding. Compressive residual stresses usually lead to performance benefits and can be introduced by shot peening, autofrettage of pressure vessels, toughening of glass or cold expansion of holes.

On a macroscopic level, thermally generated residual stresses are often the consequence of non-uniform heating or cooling operations. Coupled with the material constraints in the bulk of a large component this can lead to severe thermal gradients and the development of large internal stresses. An example is the quenching of steel or aluminium alloys, which leads to surface compressive stresses, balanced by tensile stresses in the bulk of the component. Microscopic thermally generated residual stresses can also develop in a material during manufacture and processing as a consequence of the CTE mismatch between different phases or constituents.

The chemically generated stresses can develop due to volume changes associated with chemical reactions, precipitation, or phase transformation. Chemical surface treatments and coatings can lead to the generation of substantial residual stress gradients in the surface layers of the component. Nitriding produces compressive stress in the diffusion region because of expansion of the lattice and precipitation of nitrides, and carburising causes a similar effect [19]. The magnitude of residual stresses generated in coatings can be very high – compressive stresses of the order of 6-8GPa or higher have been measured at the interface of some thermal barrier coatings (TBCs).

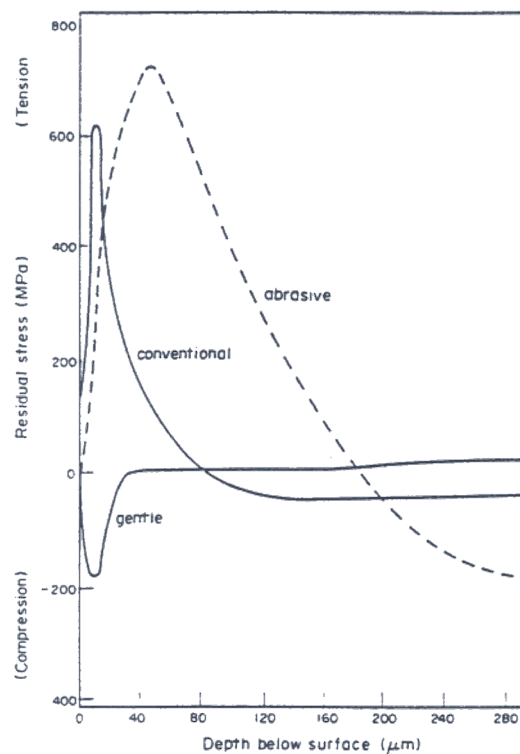


Fig 2. Characteristic residual stress distributions in a hardened steel from 3 different grinding operations [18].

2 REVIEW OF UK INDUSTRIAL SURVEY

A detailed survey covering the residual stress requirements of UK industry was carried out in August 1998 as part of an earlier NPL project funded by the DTI [20]. Over 50 completed questionnaire replies were received covering a representative cross section of UK industry and academia. Of these almost 50% indicated that residual stresses were of high importance to their business, whilst 30% ranked them as of medium importance. There was an even split between the importance of bulk and near surface residual stresses, and many organisations reported an interest in both.

The largest number of returns came from UK academia and research organisations, but there was also a high level of interest from the aerospace and power generation industries. Material manufacturers, together with the automotive and nuclear industries were well represented also. The range and size of organisations varied considerably from large multinational companies and specialised manufacturers to university departments and small consultancies.

Over 60% of the organisations who replied to the questionnaire were involved in measuring residual stress, and 30% also carried out some form of modelling. A variety of techniques were mentioned including hole drilling, X-ray and neutron diffraction, layer removal, magnetic, ultrasonic, Raman and they are ranked by their popularity below.

- Hole drilling (30%)
- X-ray diffraction (26%)
- Neutron diffraction (19%)
- Layer removal/curvature (16%)
- Other – including magnetic, ultrasonic, Raman (9%)

Many organisations used more than one technique, but there was little comment regarding the particular applications of each method, nor which technique was deemed to be the most suitable, practical and reliable for the purpose.

Most of the interest was for measurements on metals including cast iron and steels, light alloys such as aluminium, titanium and magnesium alloys, and nickel based superalloys. There was also considerable interest in all types of composite materials – metal, polymer and ceramic. Residual stress is an important issue in composite systems, particularly when the thermal expansion coefficient of the constituent phases are very different, as this can lead to the development of large residual stresses which can have a significant effect on the mechanical properties and performance.

Figure 3 overleaf shows a breakdown of the questionnaire returns

Specific comments on the industrial requirements can be grouped according to the measurement methods, manufacturing and assembly issues, and performance. Some of these are summarised below, taken directly from the questionnaire returns.

2.1 Comments on Measurement Methods

Further work is required on the cross-correlation of the different diffraction methods and on measurement reliability and interpretation.

The implications of particular levels of residual stress in different situations need to be addressed.

- *There is some concern regarding the quality of the ASTM hole drilling standard.*

New techniques for non destructive measurement of surface and subsurface residual stress would be beneficial.

Research into validation of diffraction methods is necessary. Extending the method to enable plastic deformation to be mapped would be a useful development

- *Requirement for non destructive technique for measuring residual stress in precision optical coatings and substrates.*

2.2 Comments on Manufacture and Assembly Issues

Interested in residual stress in welds and forgings, cast alloys and welds.

- *Interest in residual stresses around fastener holes that may have been cold expanded and/or contain interference fit fasteners. X-ray and neutron diffraction techniques are currently used, but a full 3D analysis is required.*

Residual stress from assembly of automotive structures, to compare mechanical fasteners and adhesive bonding

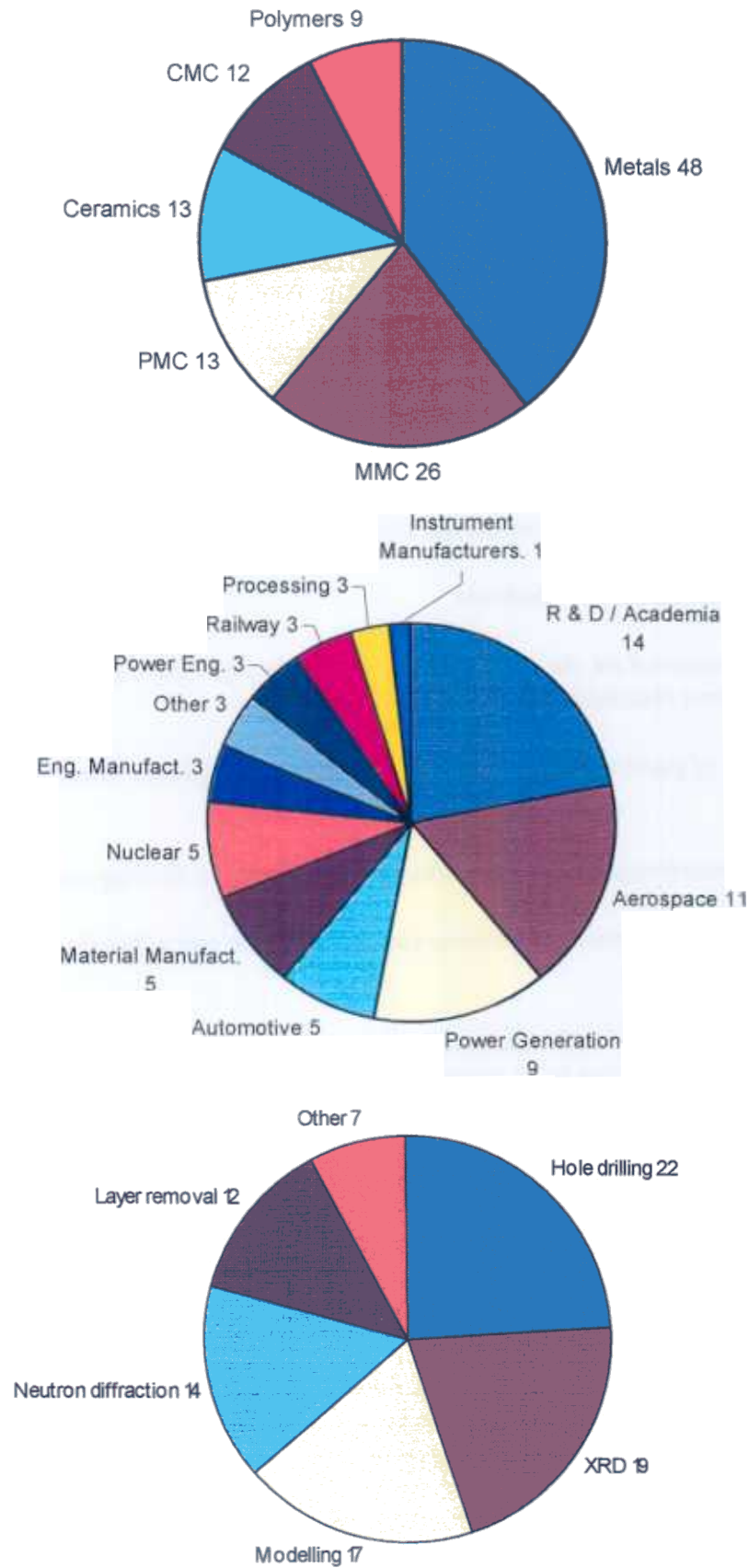


Fig 3: Breakdown of the questionnaire results according to material type, sector and measurement method

- *A general need for greater understanding with respect to design and assembly methodologies*

2.3 Comments on Performance Issues

Through thickness measurements are required to determine relaxation and redistribution of residual stress in complex geometries and the effect on crack propagation and fatigue properties.

- *Residual stress measurements on shot peened or nitrided surfaces - on real components. Results can be affected by prior stress and a tool is required to measure the change in stress.*
- *Machining of testpieces and the contribution of residual stresses to fatigue and other mechanical properties.*
- *Need to evaluate effects of residual stress during stress relief of grey cast iron and explain the effects on thermal fatigue and wear resistance.*

2.4 Other General Comments

In the UK compared with other countries (eg France, Germany, Japan) we do not utilise the potential information that can be derived from X-ray diffraction.

There is a need for modelling residual stresses generated during metal working processes.

- *Require reliable models for incorporating residual stress into component fatigue life predictions. Ideally such models should avoid having to make residual stress measurements.*

Interested in the residual stress associated with phase transformations of molten polymers, and predicting above when going from a liquid to a viscoelastic solid.

- *Require measurements of all 3 principal stresses - including radial stresses in cylinders.*

From the response to the questionnaire it is clear that residual stresses are important for a wide range of industries. The results from the survey also indicate that problems still exist with the measurement, interpretation, performance evaluation and modelling of residual stress, and some of these issues are being addressed in the current project CPM4.5 on “*Methods of Measuring Residual Stress in Components*”.

A more detailed summary of the questionnaire summary report is given in Ref. [20]

3 EXAMPLES OF TYPICAL RESIDUAL STRESS DISTRIBUTIONS

The examples below and overleaf show typical residual stress distributions for a number of key components and materials. Where appropriate the results have been taken from comparative studies to show the results from different techniques.

Fig. 4a shows an example of the stress distribution in a welded sample [45], Fig 4b the typical tangential residual stress distribution around a cold expanded hole [21] and Fig 4c shows the measured residual stresses in the individual phases of an aluminium alloy/SiC metal matrix composite across the width of a heat treated sample, showing the variation of stress across the specimen width arising from quenching [85].

Figs. 4d and 4e overleaf show 2 examples of the residual stress distributions in coated specimens [22,37] and Fig. 4f compares XRD and hole drilling measurements on a shot peened specimen [34].

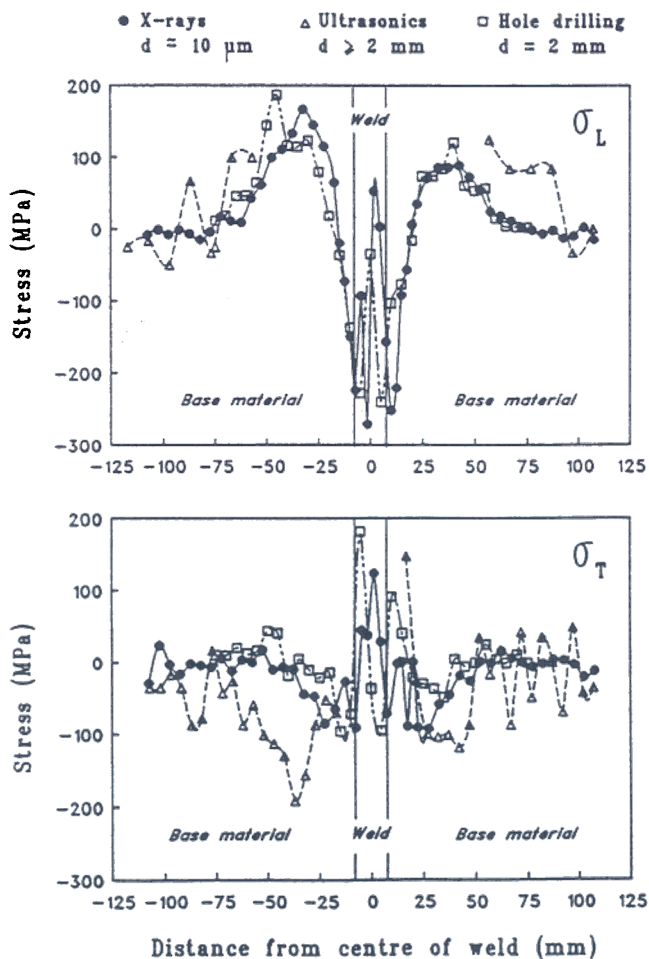


Fig 4a : Stress distribution across a weld [45]

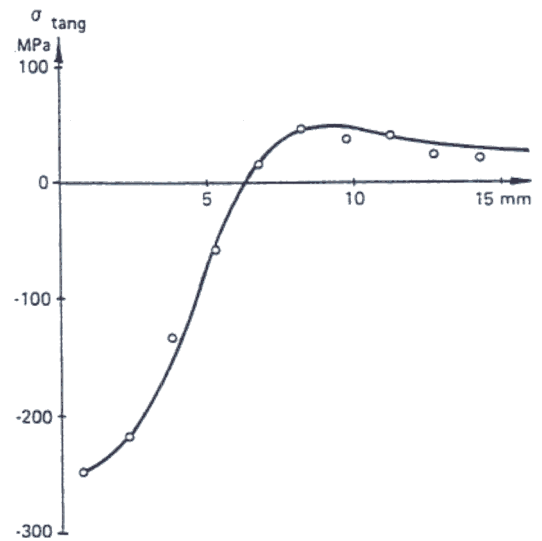


Fig 4b Example of a cold expanded hole [21]

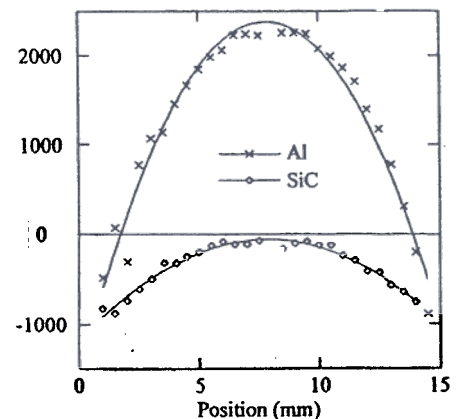


Fig 4c: Stresses in an MMC [85]

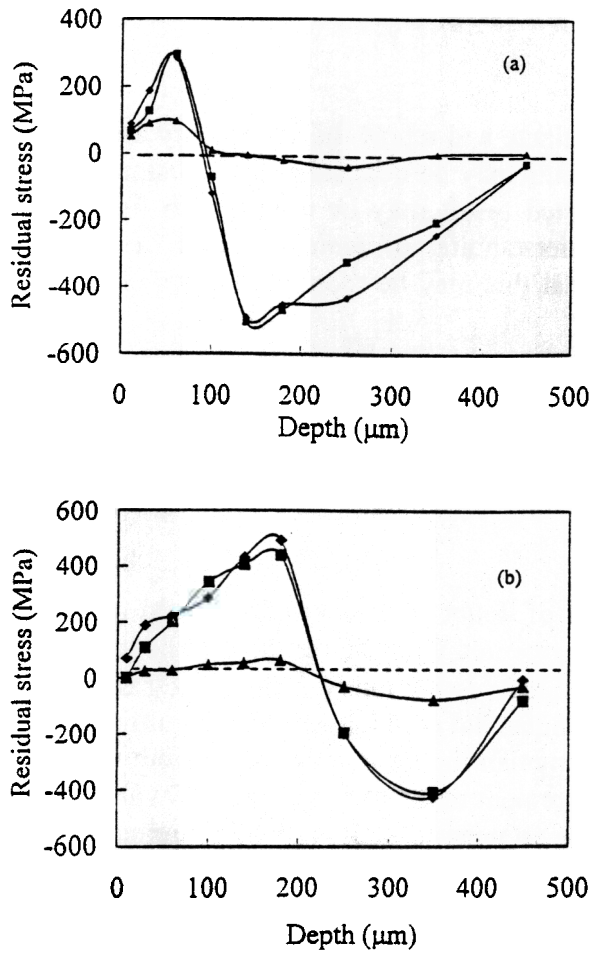


Fig 4d : Residual stresses in thick [22] plasma sprayed hydroxyapatite coatings (100 μm and 200 μm)

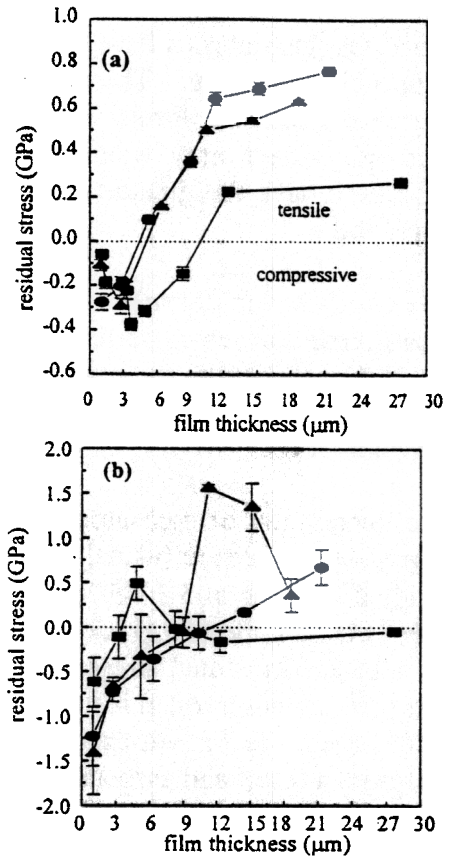


Fig 4e: Stresses in a CVD diamond film [37]

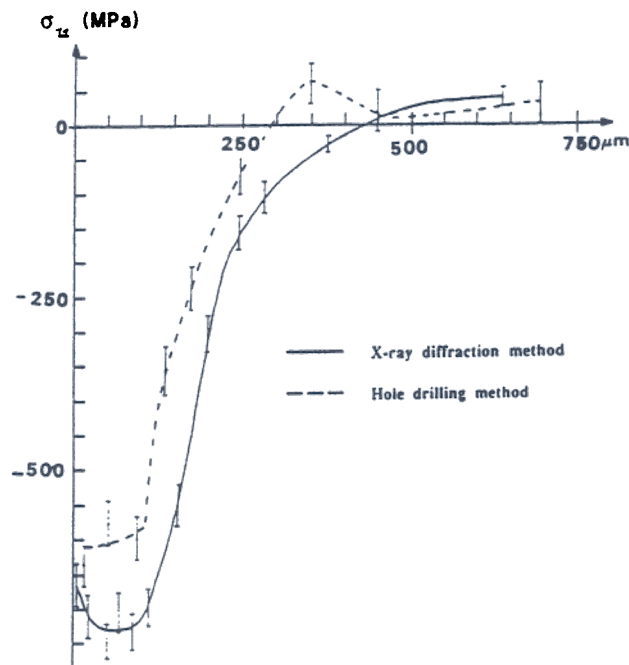


Fig 4f: Typical residual stress distribution on a shot peened specimen [34] (comparison of XRD and hole drilling)

4 ACCURACY AND UNCERTAINTY

Most test laboratories have the requirement to evaluate and report the uncertainty associated with their test results. The uncertainty measurements may be demanded by a customer who wants to know the limits within which the reported result may be assumed to lie, or the laboratory itself may want to gain a better understanding of which aspects of the test procedure have the greatest effect on results so that this may be monitored more closely or improved.

The *Guide to the Expression of Uncertainty in Measurement*, the GUM [23], states that “no measurement or test is perfect and the imperfections give rise to *errors of measurement* in the result. Consequently, the result of a measurement is only an approximation to the value of the *measurand* and is only complete when accompanied by a statement of the *uncertainty* of this approximation.”

The uncertainty of measurement defines the level of doubt in a reported result to a certain degree of confidence (usually 95%) and should be reported with the result: e.g. the measured residual stress is 505 ± 45 MPa. In this case the 45MPa is the interval about the result (505 MPa) that is expected to encompass 95% of the values that could reasonably be attributed to the measured residual stress. It is essential to distinguish the term *uncertainty* from the term *error* (in a measurement result). Error is the measurement result minus the “true” value. True values are never known exactly, or there would be no need to make any measurements, and therefore a result and associated errors can only be estimates.

The following definitions are in general agreement with References [23 and 24]

4.1 Definitions

Measurand

A measurand is the specific quantity subject to measurement. A measurand can be a direct test reading or a parameter or value determined from other readings.

Accuracy

Defines how close the test result is to the accepted “true” or reference value.

Scatter

Is the spread of results obtained from apparently identical measurements.

Uncertainty

Is the amount of doubt in a reported result. It is a parameter that defines the range within which the “true” value of a measurand is estimated to lie.

Error

Is the difference between a measurement and the “true” value of the measurand (which cannot be quantified precisely because the “true” value can never be known.)

A number of residual stress measurement methods – including XRD – produce an “error” band based on counting statistics. This “error” only reflects the scatter in the number of counts data around a mean value. It should not, therefore, be confused with the measurement uncertainty, which should reflect all sources including instrument alignment, specimen height

mis-positioning, step size, count time, 2θ range, number of ψ tilts, specimen surface texture, slit size, peak fitting method and operator errors.

4.2 Estimating Uncertainty in Residual Stress Measurement

The interpretation and uncertainty of the measurements were identified in the UK industrial survey [20] as two of the major issues that must be addressed to improve the quality and accuracy of residual stress measurements. These issues are vital if the data are to be used with confidence in design and lifetime assessment of components.

Recent advances have been made in the methods used for estimating measurement uncertainties, based on the ISO “*Guide to the expression of uncertainty in measurement*” [23]. This publication gives general guidelines on how to estimate and quantify the uncertainties associated with a particular measurement, but it is not straightforward. A simplified and more easy to follow approach has been recently produced in a European collaborative project, *UNCERT*. Within *UNCERT*, 17 separate Codes of Practice have been developed, following a common format and covering a wide range of mechanical tests. They have been published as a single volume entitled “*Manual of Codes of Practice for the Determination of Uncertainties in Mechanical Tests of Metallic Materials*” [25]. One of these Codes of Practice (CoP15) was developed for estimating the uncertainties associated with residual stress measurements made using the hole drilling technique [26], and this will be considered briefly in the next section.

Figure 5 summarises the main steps for estimating the uncertainty in accordance with the *UNCERT* manual [25].

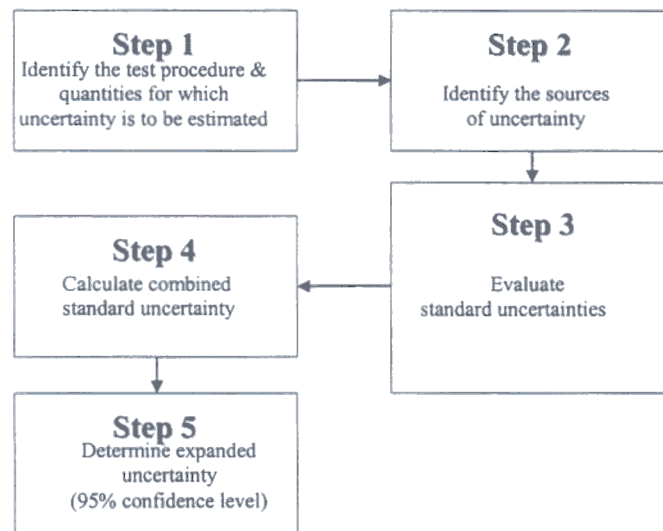


Fig 5: Steps for evaluating the uncertainty in a measurement

Steps 1 and 2 are very important in identifying the test parameters that contribute most to the uncertainty. In this first stage all input parameters should be considered including those associated with the component or material being measured, the measurement method itself, the test procedure, the operator and environment. The operator must then make some judgement as to the relative importance of each contributing parameter and the type of uncertainty.

In step 3, the standard uncertainty for each major contribution is estimated, usually from the partial derivative of the functional relationship between the output quantity (the measurand) and the input quantities. The standard uncertainty may also be obtained from appropriate experimental data, or from information provided by instrument manufacturers.

The combined standard uncertainty is then calculated in step 4 using the root sum squares of the estimated standard uncertainties, and the expanded uncertainty determined according to a specific probability or level of confidence (usually 95%) in step 5. This expanded uncertainty is defined as the interval about the result of a measurement that describes the amount of doubt associated with the result.

The result should be quoted in the form $V = y \pm U$

..... where V is the estimated value of the measurand, y is the measurement result and U is the expanded uncertainty associated with y .

4.3 Identifying the Uncertainties in Hole Drilling – an Example

The table overleaf shows an example assessment sheet from the UNCERT CoP15 [26], which has been developed for estimating the uncertainties associated with the hole drilling technique. The document is still under development and has been published as a first working draft. The table lists the typical sources of uncertainty and their likely contribution to the residual stress measurement. It can be used to identify which parameters have a major contribution to the uncertainty in the measurement, which have only a minor effect and those that are considered negligible and can be disregarded. It is a vital step in understanding the sources of the uncertainties and, by identifying the major contributions, experiments or equipment can be redesigned to reduce their effects.

The list given in the table is by no means exhaustive and a further survey of hole drilling practitioners identified some of the other issues that may be important, including

- Drilling method
- Drill speed and feed
- Operator skill
- Gauge factor
- Quality of gauge installation
- Eccentricity, concentricity & target positioning
- Instrumentation resolution, accuracy and linearity
- Quality of gauge installation
- Drill wear
- Data reduction methods
- Excitation voltage
- Induced temperature rises

For hole drilling, it is also likely that different uncertainty budgets will apply to measurements in the field and in the laboratory.

In determining the uncertainties in the measurement all parameters should be considered. Rather than duplicate exactly what is in the table it is good practice for each user to follow through the process of analysing and estimating the uncertainties associated with their own particular set up, measurements and equipment.

Typical sources of uncertainty and their likely contribution to uncertainties in residual stress measurement by the hole drilling method. See Ref 26 for full details.

Source of uncertainty	Type	Measurands		Measurements				
		$\sigma_{\max}$ $\sigma_{\min}$	β	E	μ	$\varepsilon_{1,2,3}$	D_o	D
1. Test piece								
Surface finish	B	2	2			2	2	2
Material characteristics	B	1	1	1	1	1		
2. Test system								
Hole Alignment								
Measurement of hole dimensions	A or B	1					1	
Gauge circle dimensions	B	1						1
Uncertainty in strain measurement	B	1	1			1		
Drift in strain measuring system	B	2	2			2		
Stress and temperature resulting from drilling	B	2	2			2	2	2
3. Environment								
Temperature and humidity	B							
4. Test Procedure								
Calculation of $\bar{A}$,	B	1	1	1	1			
Calculation of $\bar{B}$	B	1		1				
$\bar{a}$	B	1					1	1

[1 = major contribution, 2 = minor contribution, blank = insignificant contribution]

The component uncertainties are then evaluated by the appropriate method and each is expressed as a **standard deviation**. This is referred to the **standard uncertainty**.

In the example above the terms $\bar{A}$, and $\bar{B}$ are used in the analysis equations for calculating residual stresses in hole drilling and should not be confused with the Type A and B uncertainties.

Generally, the results of the measurements are given as a single unique value for a particular set of conditions. Apart from the inevitable differences between test laboratories using the same technique [27,28], the results in this form do not give any information on the uncertainties associated with the measurement. Such results may be adequate for comparative purposes but they are not satisfactory when the customer requires an absolute measurement of the residual stress and the associated uncertainty that could be expected at a particular location in a material. To do this a thorough examination should be made of the experimental

test set up and measurement method. Very few residual stress measurement techniques have been considered in sufficient detail at present to satisfy this requirement, but one approach to achieving this goal is to develop, for each test method, a robust procedure that would establish the following:

- Terminology
 - Detailed measurement procedure
 - Exact definition of the test result and how to report and interpret it
- Uncertainty statement in accordance with a clear and commonly agreed methodology

VAMAS TWA20 is addressing this issue in the new standard for neutron diffraction that is currently in preparation [29]. A similar approach is being adopted in the current DTI-funded project at NPL to quantify in more detail the uncertainties associated with the XRD and hole drilling techniques.

5 GUIDE TO TECHNIQUE SELECTION

The technique selector is aimed primarily at readers who do not have an extensive knowledge of residual stress measurement. It can be used to provide guidance on the specific applications of the commonly available techniques and their basic attributes. An on-line interactive version, which can be found at <http://www.npl.co.uk/materials/residualstress/> is being developed as part of the NPL Residual Stress website, and will be linked to a register of UK experts and facilities.

5.1 Introduction

To aid selection three tables have been designed to address some of the important issues that should be considered when choosing a technique. Only the more commonly available techniques are considered and the Tables only provide the first stage of technique selection. Where appropriate, absolute values or a range of values are given, but where that is not possible general comments are included to aid comparison.

Table 1 – Practical Issues which deals with matters such as the cost, availability of equipment, portability, measurement speed, existence of a standard procedure and the level of expertise required.

Table 2 – Material Issues - covers material related factors such as the class of materials that can be examined with a particular technique, required property information, surface preparation etc.

Table 3 – Measurement Characteristics – includes information on the physical characteristics of each technique including the resolution, penetration, stress-averaging area or volume, stress type, stress state, stress gradient and uncertainty.

A summary table (Table 4) is also included detailing the specific advantages and limitations of the various techniques.

5.2 How to use the Tables

It is probably a good starting point to consider Tables 1 and 2 together as these deal with some of the more practical issues associated with the measurement and the compatibility with material type. Some of the issues (e.g. whether a particular technique is destructive, non-contacting, lab-based or portable) can be used directly for selection; others (such as cost of equipment, availability and speed) are for comparison purposes.

Even at this first stage several techniques will probably be eliminated.

The class of material or size of the component can be used as the first stage of technique selection as these will probably eliminate a number of techniques that are unsuitable. The term *Structures* refers to large components such as pipework, bridges and large items of machinery in the field that cannot be moved from the site for measurement and a portable technique is therefore required; *Artefacts* are small components which can be brought into the laboratory for testing.

Most of the techniques are considered to be non-destructive. Hole drilling is often classed as semi-destructive because a small hole is drilled into the component. This can often be tolerated or repaired in large structures but the implication of the hole depends very much on the size and nature of the component being measured. Layer removal is destructive as are other techniques that require the component to be dramatically modified in any way to fit the equipment and after which it cannot be put back into service. Some techniques require surface preparation and even light abrasion or cleaning of the surface will be considered destructive in certain situations. In these cases, where the user does not want any damage or changes to the specimen, consideration should be given to using those techniques which require little or no surface preparation and are non-destructive.

Inexperienced users should note that any changes to the component, in terms of surface preparation, machining or sectioning can seriously affect the internal stress distribution and subsequent measurements will not reflect the original residual stress state present.

The *availability of equipment* is loosely linked to *equipment costs* and gives some indication of the number of measurement facilities. Speed refers to the time taken to carry out a basic measurement, but the turnaround may be an important factor also. This is a particular issue when specialist facilities such as neutron diffraction and synchrotron are being considered as often beam time must be booked on the instrument several months in advance.

It has proved very difficult to get specific details on costs. *Equipment costs*, which are only really relevant if the user wants to set up a measurement facility, have been classified as low, medium and strategic. The latter refers to centrally funded Government facilities to which the customer may have access. The *cost of measurement* may reflect the cost of equipment but not in all cases. The figures quoted in Table 3 are designed to reflect the cost of a basic measurement. Sophisticated 3D strain mapping, 2D measurements and depth profiling are possible with a number of the techniques, but the cost of these type of measurements are not considered. Table 3 gives more specific detail on the physical characteristics of the various techniques. The values quoted for *resolution* and *penetration* have been taken from the literature and give a comparison of the capabilities of the different techniques. Where appropriate values for particular materials are quoted.

Table 4 summarises the advantages and disadvantages of the various techniques.

Technique Selector: Table 1 - Practical Issues

Key Techniques	Practical Issues									
	Size of Component	Contact or Non contact	Destructive?	Lab based or portable	Availability of equipment	Speed	Standards available	Cost of Equipment	Cost ¹ of Measurement	Level of Expertise Required
Hole Drilling	Structures Artefacts Coatings ²	Contact	Semi	Both	Widespread	Fast/Med	ASTM E837-99 ⁴	Low	£50 - 200	Low/Med
X-ray Diffraction	Structures Artefacts Coatings	Non-contact	No ³	Both	Generally available	Fast/Med	No ⁴	Med	£50 - 200	Med
Synchrotron	Artefacts Coatings ²	Non-contact	No	Laboratory	Specialist	Fast	No	Strategic /Government facility ⁵	High (Exact range is not available)	High
Neutron Diffraction	Artefacts	Non-contact	No	Laboratory	Specialist	Med/Slow	No ⁶	Strategic /Government facility ⁵	£10 – 1500	High
Curvature and Layer Removal	Artefacts Coatings	Contact	Yes	Laboratory	Generally available	Med	No	Low	£50 - 200	Low/Med
Magnetic	Structures Artefacts	Non-contact	No	Both	Generally available	Rapid	No	Med	Low (Exact range is not available)	Low
Ultrasonic	Structures Artefacts	Contact	No	Both	Generally available	Rapid	No	Med	Low (Exact range is not available)	Med
Raman/ Fluorescence	Structures Artefacts Coatings	Non-contact	No	Both	Generally available	Fast	No	Med	Low (Exact range is not available)	Med

1 Depending on the type of instrument used, size and geometry of sample and, whenever relevant, number of counts required.

2 Thick coatings only.

3

Can be destructive if used for depth profiling.

4 Two Good Practice Guides (for XRD and Hole drilling) are being developed as part of this project.

5 These facilities are of strategic infrastructure nature that are funded either by government or inter-government agencies.

6 An international standard protocol is being prepared by VAMAS TWA20.

Technique Selector: Table 2 - Material Issues

Key Techniques	Material Issues					
	Material Type	Composites	Crystalline or amorphous	Coated?	Surface preparation	Surface condition
Hole Drilling	Metals Plastics Ceramics	Yes	Either	Yes	Light abrasion – strain gauge	Flat – Preparation must not affect stresses.
X-ray Diffraction	Metals Ceramics	Yes	Crystalline	Yes	Important	Important
Synchrotron	Metals Ceramics	Yes	Crystalline	Yes	Important	Not critical.
Neutron Diffraction	Metals Ceramics	Yes	Crystalline	No	Not critical	Not critical
Curvature and Layer Removal	All	Yes	N/A	Yes	Not critical	Not critical
Magnetic	Ferromagnetic Materials ¹	No	Crystalline	No	Not critical	Not critical
Ultrasonic	Metals Ceramics	Yes	Crystalline	Yes	Not critical	Not critical
Raman/Fluorescence	Ceramics Polymers	Yes	Either	Yes	Not critical	Not critical

Highly sensitive to microstructure – second phases, dislocations, inclusions etc.

Technique Selector: Table 3 – Physical Characteristics

Key Techniques	Physical Characteristics							
	Resolution	Penetration	Stress Type	Stress State	Stress gradient	Uncertainty	Sampling Area /Volume	Remarks
Hole Drilling	50-100 μm depth increment	= hole diameter	Macro	Uniaxial Biaxial	Yes – difficult to interpret	Varies with depth	1-2 mm diam. 1-2 mm deep	
X-ray Diffraction	20 μm depth 1mm laterally	5 μm – Ti 50 μm – Al 1mm – layer removal	Macro Micro	Uniaxial Biaxial	Yes – with layer removal	Limited by several factors	0.1-1 mm^2 0.05-0.1 mm	Resolution for steel 1 mm diameter (min) 15 μm depth
Synchrotron	20 μm lateral to incident beam. 1 mm parallel	>500 μm 100 mm - Al	Macro Micro	Uniaxial Biaxial Triaxial	Yes	Limited by grain sampling	0.1 mm^3	Measures strain only. Rarely possible to obtain stresses.
Neutron Diffraction	500 μm	100 mm – Al 25 mm – Fe 4 mm - Ti	Macro Micro	Uniaxial Biaxial Triaxial	Yes	Limited by number of counts	>1 mm^3	
Curvature and Layer Removal	Depends on material & measurement method	Not applicable	Macro	Uniaxial Biaxial	Yes			Layer removal can be combined with other measurement methods such as XRD and magnetic to give information on stress profiles
Magnetic	1 mm	20-300 μm (Barkhausen)	Macro	Uniaxial Biaxial	No		>2 mm^2	Sensitive to microstructure, anisotropy and texture.
Ultrasonic	5 mm	> 100 mm along specimen	Macro	Uniaxial Biaxial	No		1-400 mm^2	
Raman/ Fluorescence	0.5 μm	Surface	Macro	Uniaxial Biaxial				

Table 4: Advantages and disadvantages of the various techniques

Technique	PROs	CONs
Hole Drilling	• Quick, simple, • Widely available • Portable. • Wide range of materials • Deep hole drilling for thick section components	• Interpretation of data • Destructive • Limited strain sensitivity and resolution
X Ray Diffraction	• Versatile,widely available • Wide range of materials • Portable systems • Macro and micro RS	• Basic measurements • Lab-based systems, small components
Synchrotron	• Improved penetration & resolution of X-rays • Depth profiling • Fast • Macro and micro RS	• Specialist facility only • Lab-based
Neutron Diffraction	• Excellent penetration & resolution • 3D maps • Macro and micro RS	• Specialist facility only • Lab-based
Curvature and Layer Removal	• Relatively simple • Wide range of Materials • Can be combined with other techniques to give stress profile	• Limited to simple shapes • Destructive • Lab-based
Magnetic	• Very fast • Wide variety of magnetic techniques • Portable	• Can apply to ferromagnetic materials only • Need to separate the microstructure signal from that due to stress
Ultrasonic	• Generally available • Very fast • Low cost • Portable	• Limited resolution • Bulk measurements over whole volume
Raman/Fluorescence	• High resolution • Portable systems available	• Surface measurements • Interpretation • Calibration • Limited range of materials

Most techniques have the capability to measure the macroscopic residual stresses in a component but only XRD, neutron diffraction, synchrotron and Raman have the necessary resolution to measure the micro residual stresses generated within the microstructure of a material.

The uncertainty in the measurement is an important issue, but one which has received relatively little attention. There are both physical limitations and practical factors that affect the measurement and both should be considered in developing an uncertainty budget. Within the current NPL DTI-funded project the XRD and hole drilling methods are being investigated and two separate Good Practice Guides will be produced which will provide advice and information on the recommended test methodology and uncertainty measurement.

A more detailed examination of the XRD technique is also being carried out to quantify and validate the contribution of some of the key experimental parameters to the scatter, accuracy and uncertainty. As an example, Figure 6 shows the results from a series of 10 repeat measurements at the same point on a shot peened steel specimen to compare the peak fitting routines. The specimen was not moved between measurements and clearly the choice of peak fitting routine has an influence on the repeatability of the measured values. To confirm the validity of this approach tests are currently being repeated on a variety of industrially relevant materials.

5.3 Comparative Studies

An intercomparison exercise is also being undertaken in the present work, examining the application of up to 7 different techniques applied to a shot peened steel, heat-treated aluminium and a TiN coated specimen. Figure 7 shows some of the preliminary results on the shot peened steel from 7 laboratories using XRD. For each specimen, the residual stress was measured at NPL prior to distribution and these are also included in Fig.6 for comparison.

A number of intercomparison exercises have been carried out and reported in the literature to compare different techniques and laboratories. Some of the key publications are summarised in Table 5. It is difficult to make direct comparisons between all the techniques since the characteristic volume of material and the depth of measurement varies significantly. In general there was good agreement between the x-ray diffraction results and the hole drilling measurements made close to the surface. Similar comparisons could be made with hole drilling and neutron diffraction measurements to a limited depth. Only the exercise organised by ASTM, and detailed in Ref. 27 included a significant number of different laboratories and techniques most of the other measurements were made at a single organisation.

Results from a French inter-laboratory comparison, involving 16 laboratories using 21 different XRD instruments [28], gave an inter-laboratory average value of σ_{11} of -469 MPa and the standard deviation was ± 36 MPa. The results indicated that the largest sources of error in the measurement were associated with the peak fitting software and the operator.

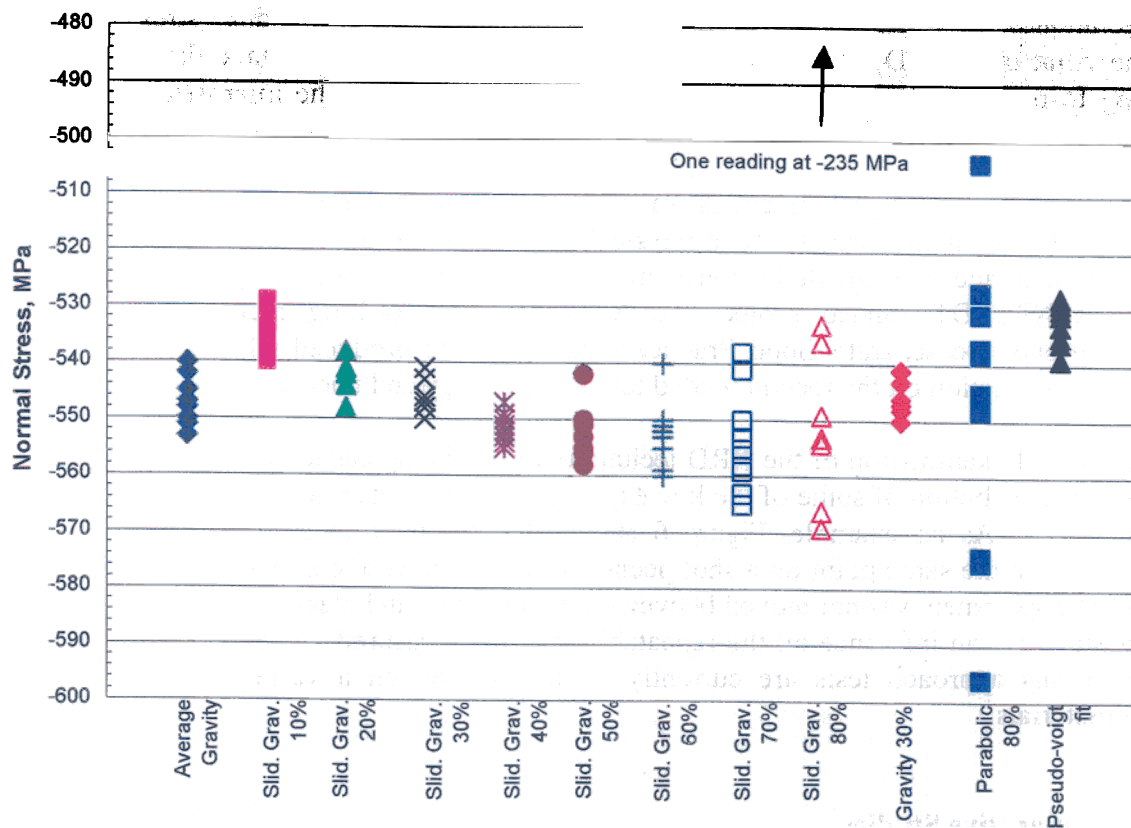


Fig 6: Comparison of different peak fitting routines (Shot peened spring steel)

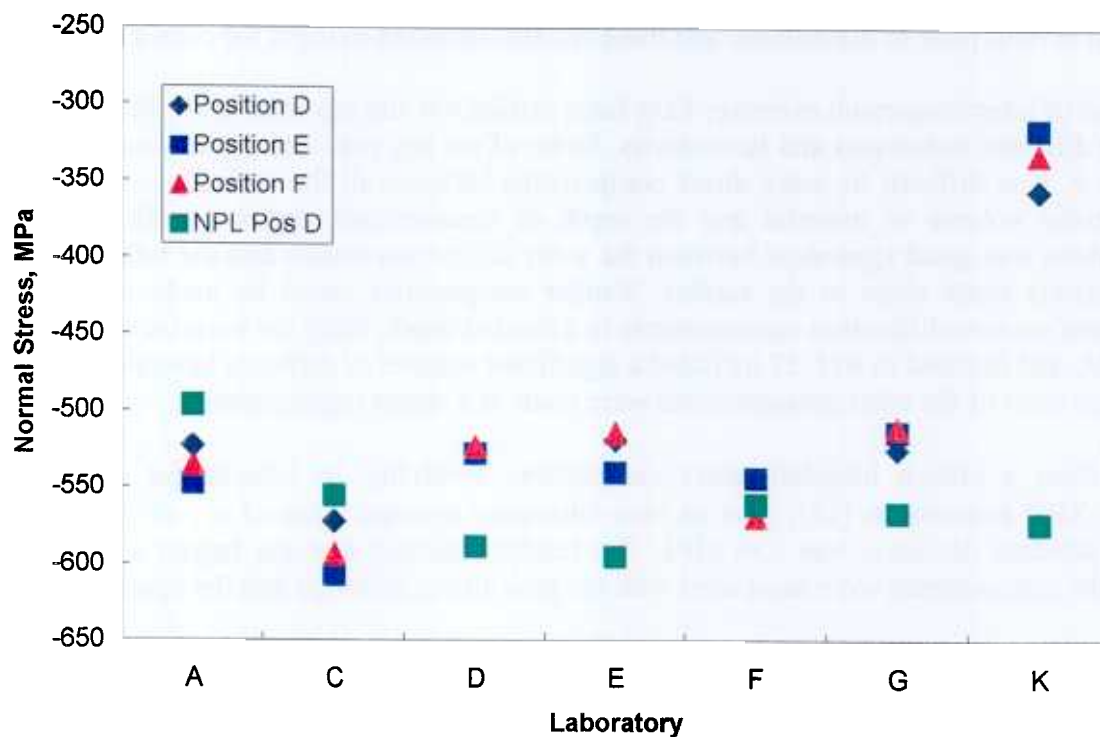


Fig 7: XRD measurements from 7 laboratories in NPL round robin exercise on a shot peened spring steel

Table 5: Summary of Comparative Studies

Techniques compared *	Material	Ref	Comments
HD, XRD, LR, U	AISI 304 stainless steel	27	ASTM exercise. Over 50 stress-free samples were measured by 35 participants. Good agreement except for the low speed end mill HD technique, which gave results of ~ 330 MPa
XRD, ND, HD	Electron beam welded plate – WASPALOY	30	Texture in weld metal precludes use of XRD, good in HAZ. Plane strain assumption for ND invalid, HD measurements in the weld area were unreliable.
XRD, ND	Zirconium alloy tubes	31	Strains were too small to make an accurate comparison.
XRD, LR	Steel (42CrMo4)	32	XRD agreed well with the LR results for surface measurements
XRD, HD, BN	Mild steel bar	33	Excellent agreement between the HD and XRD. The magnetic BNA method gave poor correlation with the XRD due to the sensitivity of the BNA to the sample texture.
XRD, HD	Titanium alloy, stainless steel & nickel alloy (IN100)	34	Reasonable agreement between XRD and HD techniques for all materials
ND, M	Welded steel plate	35	The example of residual stress measurements perpendicular to the weld line showed remarkable agreement between the magnetic and ND techniques.
XRD, I	Aluminium film	36	Continuous indentation and XRD techniques were used to follow stress relaxation of heat treated aluminium films of various thickness. Both methods gave similar results for films up to 0.5 µm thick but were less satisfactory with thicker films.
C, XRD, R	CVD diamond films	37	Considerable differences in results from the 3 methods used.
ND, XRD	Metal matrix composite	38	Poor agreement.

* Key overleaf

Table 5: Summary of Comparative Studies (contd)

Techniques compared	Material	Ref	Comments
ND, M	Steel (weld)	39	Stress values measured from two combinations of magnetic techniques showed satisfactory levels of agreement with the ND measurements
BN, XRD	Welded metal sheets	40	XRD used for calibration of the BNA technique
XRD, ND, HD	Shot peened steel and Ni superalloy	41	Good agreement in the interior of the material, some discrepancies in the surface layers.
U, HD	Welded steel plates	42	Ultrasonic measurements used for measuring stress before and after stress relief. HD results affected by surface preparation.
ND, XRD, HD	High strength steels	43	ND was most suitable for determining the 3 principal stresses in the bulk, XRD and HD good for surface and subsurface, Applicability depends on the magnitude and location of residual stress.
XRD, HD	Ti alloy, martensitic steel, nickel alloy	44	Good agreement and similar scatter for the 2 techniques. XRD allowed stresses in individual phases to be measured.
XRD, HD, U	TIG welded steel and stainless	45	XRD and HD gave excellent agreement, Ultrasonic results showed considerable scatter
XRD, HD, ND	Plasma sprayed metallic and ceramic coatings	46	Qualitative agreement only
XRD, HD	Shot peened 6082 Al alloy	47	Good comparison between XRD and HD. Examples of different HD analyses (Integral, linear, cubic spline)
Nano, EBSP	Ni-based superalloy, Al, Waspaloy	49	Interim results. Grain imaging represents a useful technique for locating regions of deformation.

Key: HD Hole drilling XRD X-ray Diffraction ND Neutron Diffraction R Raman
 LR Layer Removal U Ultrasonics BN Barkhausen Noise
 C Curvature M Magnetic I Indentation
 Nano Nanoindentation EBSP Electron Backscattered Patterns

An international investigation under the auspices of VAMAS TWA20 (Versailles Project on Advanced Materials and Standards, Technical Working Area 20) for residual stress measurements in crystalline materials by neutron diffraction is currently being carried out on 4 separate artefacts – a shrink-fit ring and plug assembly, ceramic matrix composite, shot-peened plate and a ferritic steel weldment [29]. Measurements on a shrink-fit ring and plug assembly have been completed and show that strain can be determined to an accuracy of 10^{-4} , which corresponds to a resolution in stress of ± 7 MPa, and a positional tolerance of ± 0.1 mm [29].

Work is in progress towards preparing an international protocol with the aim of publishing it as Technology Trends Assessment (TTA) by ISO in 2001.

The main conclusions that can be drawn from the above studies are that different techniques may not produce the same result and that inter-laboratory variability is unacceptably high. With the exception of the results reported in the neutron diffraction studies, the scatter and reliability of the results obtained from almost all the other techniques was considerable. It is reasonable to conclude that there should be greater emphasis on obtaining an improved understanding of the measurement methods, better interpretation of their results and credible procedures for estimating the associated uncertainties.

Results from the intercomparison exercise and detailed uncertainty evaluation being carried out under the present work will be used to develop a Good Practice Guide for using XRD for residual stress measurements. The document will provide a UK input into the CEN working group who are active in developing a European standard in this area.

A separate Good Practice Guide on Hole Drilling will also be produced.

6 BACKGROUND TO MEASUREMENT TECHNIQUES

A wide variety of residual stress measurement techniques exist, but only those identified in the UK industrial survey are considered here. Each section gives some basic information about the technique, highlighting some of the key attributes, advantages and disadvantages. Key references are given as appropriate.

6.1 Hole Drilling

Hole drilling is one of the most widely used techniques for measuring residual stress. It is relatively simple, cheap, quick and versatile. Equipment can be laboratory-based or portable, and the technique can be applied to a wide range of materials and components.

The principle of the technique involves the introduction of a small hole into a component containing residual stresses and subsequent measurement of the locally relieved surface strains. The residual stress can then be calculated from these strains using formulae and calculations derived from experimental and Finite Element Analyses. In practical terms, a hole is drilled in the component at the centre of a special strain gauge rosette. Close to the hole, the strain relief is nearly complete but the technique suffers from limited strain sensitivity and potential errors and uncertainties related to the dimensions of the hole (diameter, concentricity, profile, depth etc.), surface roughness, flatness, and specimen preparation. Incremental hole drilling improves the versatility of the technique and enables stress profiles and gradients to be measured.

Figure 8 shows a typical commercially available hole drilling rig and gauge geometry. Since any residual stress created by the drilling process will adversely affect the results, it is important that a suitable drilling method be chosen. These include the use of conventional drilling, abrasive jet machining and high speed air turbines.

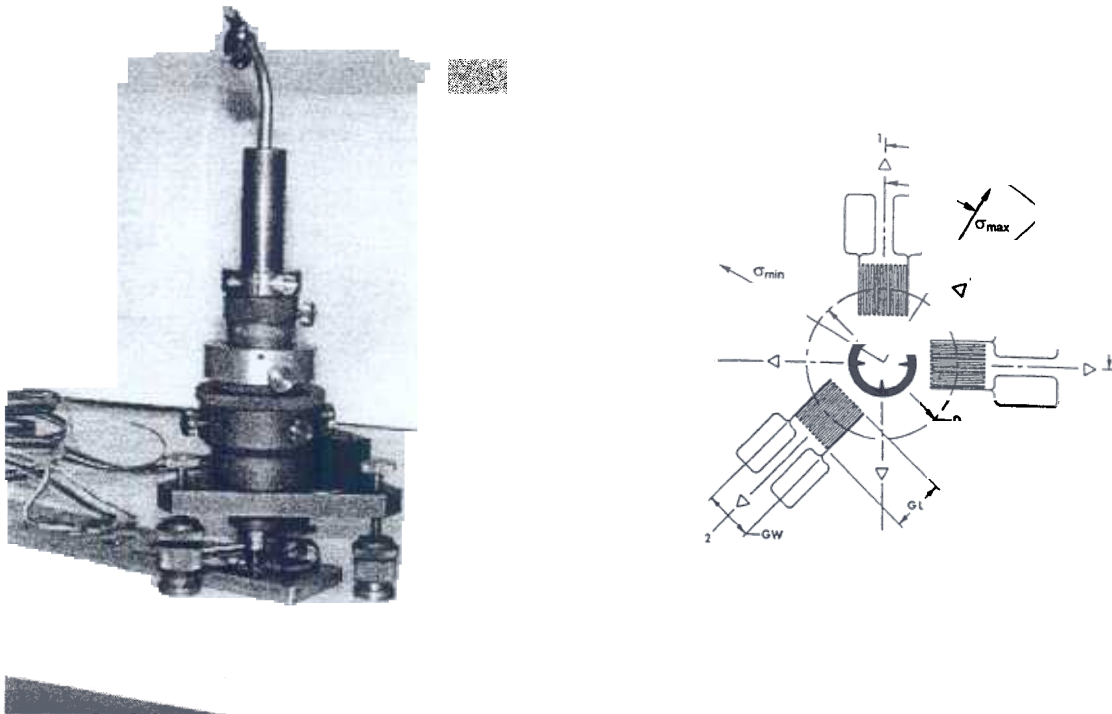


Fig. 8 Typical hole-drilling apparatus and residual stress strain gauge rosette design

In practical terms there is no point making measurements beyond a depth roughly equivalent to the drill diameter, since no additional strain can be measured. The basic hole drilling analysis assumes that the material is isotropic and linear elastic, that stresses do not vary significantly with depth and the variations of stress within the body of the hole are small. The basic analysis only applies where residual stress values do not exceed half the yield strength of the material.

Figure 9 shows a range of residual stress strain gauge geometries currently available. Strain gauge type A is the most commonly used design and is recommended for general purpose measurements, Type B is useful where measurements need to be made near an obstacle or close to a fillet or radius. Type C, which uses 6 grids, has been introduced recently to give improved strain sensitivity.

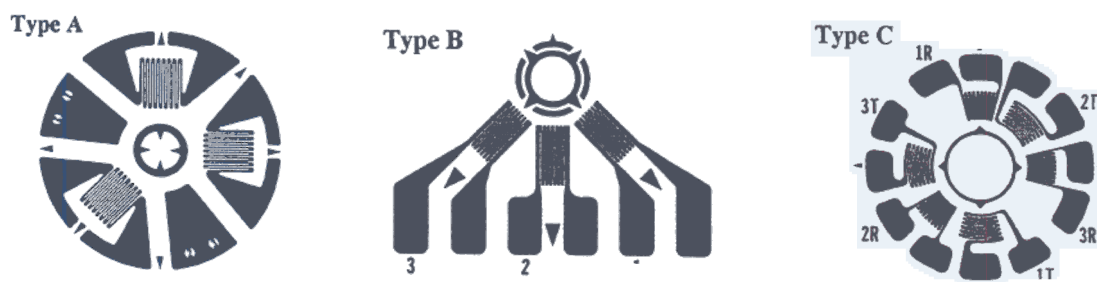


Fig. 9 Typical residual stress strain gauge rosette geometries

With hole drilling some surface preparation is required to achieve good bonding of the strain gauges, but care must be taken not to remove too much material particularly if the residual stresses close to the surface are important. Choosing a suitable strain gauge and drill size is important (and the two are closely linked) because this will determine the maximum depth of the measurement. Gauge size is important and should be considered in relation to the type of stresses present. Small gauges give a more localised measurement, but are more difficult to handle, only give limited depth information (because of the corresponding small drill size) and are possibly susceptible to larger errors associated with misalignment or surface irregularities. Some key references on the subject [50-55] are included for further information.

The hole drilling technique is open to a certain amount of criticism. Although there is a Standard for hole drilling – ASTM E837-99, the applicability is limited only to basic measurements where the stress field is essentially uniform. Other analysis methods – such as the Integral and Power series techniques - have been developed for calculating the residual stress distributions in non-uniform stress fields where ASTM E837 does not strictly apply [56-59]. Based on solutions of FE calculations the *Integral Method* is best for highly non-uniform stress fields where the individual contribution to the measured strain is identified at each depth increment. The main limitation is that the residual stresses are assumed constant with each depth increment. A *Power Series* solution can be used when the residual stresses vary smoothly with depth. Ref. 46 give an example of the different analysis solutions.

Despite some shortcomings the hole drilling technique remains a popular means of measuring residual stress. Recent developments include the introduction of new rosette designs, and the development of laser speckle interferometry, Moiré interferometry and holography for carrying out full field measurements [60-63]. Other improvements include the

application of the technique to thick coatings and materials with non-uniform and severe stress gradients, and novel drilling techniques to increase the strain sensitivity and reliability of the measurements [64,65].

Important issues related to the interpretation of results must be addressed, and guidelines will be included in the *Hole Drilling Good Practice Guide* that is being developed as part of the current work.

Deep Hole Drilling is a variation of the technique which has been developed for measuring residual stresses in thick-section components. The method was originally developed in the 1970s by Beany [66] and Zhdanov and Gonchar [67], but has undergone considerable development since [68-71]

The basic procedure involves drilling a small reference hole through the specimen and subsequent removal of a column of material, centred about the reference hole, using a trepanning technique. The diameter of the reference hole is measured accurately along its length before the column is machined out. When the column is removed the stresses relax and the reference hole diameter and column dimensions change, the dimensions of the column and reference hole are then re-measured and the residual stresses calculated from the dimensional changes caused by removing the material from the bulk of the specimen.

In measurements on welded specimens [71] reference hole diameters of 3.175 mm have been used with a column diameter of 20mm. Measurements of the diameter were made at intervals of 0.2 mm. Using this technique the through thickness residual stress distribution can be measured on specimens up to 100 mm thick.

The deep-hole drilling technique has been used to measure residual stresses in thick sections of complex shape, but there is limited agreement at this stage between experimental measurements and finite element predictions.

6.2 X-Ray Diffraction

X-Ray diffraction relies on the elastic deformations within a polycrystalline material to measure internal stresses in a material. The deformations cause changes in the spacing of the lattice planes from their stress free value to a new value that corresponds to the magnitude of the applied stress. This new spacing will be the same in any similarly oriented planes, with respect to the applied stress and the crystal lattice therefore effectively acts as a very small strain gauge. The measurement itself is relatively straightforward and equipment readily available. During a measurement the specimen is irradiated with high energy X-rays that penetrate the surface, the crystal planes diffract some of these X-rays, according to Bragg's law and a detector, which moves around the specimen (see Figure 10) to detect the angular positions where diffracted X-rays are located, records the intensity of these rays at that angular position. The location of the peaks enable the user to evaluate the stress within the component.

Several experimental methods can be used to evaluate the stresses within a material using this diffractometer technique, including:

- the two-exposure method
- parallel-beam method

- $\text{Sin}^2 \psi$ method
- side-inclination method
- and a variant of the two-exposure method whereby the inclined measurement is made at $\psi = 60^\circ$ rather than at 45° .

The most popular method is probably the $\text{Sin}^2 \psi$ method. This has the advantage that inclined measurements are made at a number of angles ψ rather than at only one. Values of the lattice spacing, d_i , or $2\theta_i$ are plotted against $\text{Sin}^2 \psi$, and the stress σ_ϕ is derived from the slope of the line, or elliptical fit.

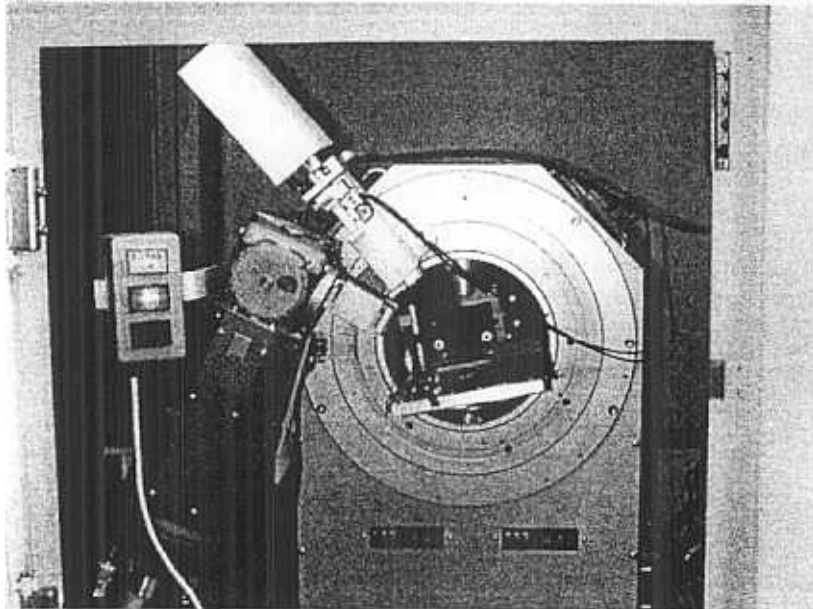


Fig. 10 Practical example of a diffractometer, showing the X-ray source, sample stage, detector and goniometer

The goniometer's alignment can be verified using a stress-free sample such as a powder or a quartz block. The diffractometer scans the output to define the position of the peaks which can be compared to known peaks on the JCPDS database. The closeness of the results defines the instrument alignment. If unsatisfactory the alignment can be readjusted and then re-verified.

XRD can be considered to be a non-destructive technique for measuring surface stresses. It can be combined with some form of layer removal technique so that a stress profile can be generated, but then the method becomes destructive.

One of the major disadvantages with XRD is the limitation imposed on the test piece size and geometry. The geometry has to be such that an X-ray can both hit the measurement area and still be diffracted to the detector without hitting any obstructions. Problems may also occur if the surface is too rough, so surface condition is a consideration. Size may also be a problem, because the entire artefact or component must fit into the diffractometer. Portable diffractometers are now available which can be taken out into the field for measurements of structures such as pipelines, welds and bridges. The speed of measurement depends on a number of factors including the type of material being examined, the X-ray source and the

degree of accuracy required. With careful selection of the X-ray source and test set-up this can be minimised and new detector technology has also greatly reduced the measurement time. X-ray diffraction has a spatial resolution of 1–2 mm down to tens of μm s and a penetration depth of around 10 – 30 μm , depending on the material and source.

Some key publications are presented in Refs [72-84].

Synchrotron

Synchrotrons, or hard X-rays, provide very intense beams of high energy X-rays. These X-rays have a much higher depth penetration than conventional X-rays, typically around 50 mm in aluminium. This increased penetration depth means that synchrotron diffraction is capable of providing high spatial resolution, three-dimensional maps of the strain distribution to millimetre depths in engineered components.

This increased penetration depth is one of the major advantages of synchrotron diffraction over the more conventional X-ray diffraction. Another great advantage that synchrotrons have is that intense narrow beams of 1mm-10 μm in size are possible. This leads to spatial resolutions that are limited not by the instrument but by the crystallite size within the sample. The measurement is also very much quicker than with conventional X-ray diffraction. With measurements times of a fraction of a second, detailed strain maps of components can be constructed using a few hours of beam time.

Presently, synchrotron diffraction is only available at central facilities, in much the same way as with neutron diffraction. Two such facilities are the European Synchrotron Research Facility in Grenoble, and the SRS in Daresbury. For further reading see Refs 85-88.

Neutron Diffraction

Like other diffraction techniques neutron diffraction relies on elastic deformations within a polycrystalline material that cause changes in the spacing of the lattice planes from their stress free value. Measurements are carried out in much the same way as with X-ray diffraction, with a detector moving around the sample, locating the positions of high intensity diffracted beams. The greatest advantage that neutrons have over X-rays is the very large penetration depths that neutrons can obtain, which makes them capable of measuring at near surface depths of around 0.2mm down to bulk measurements of up to 100mm in aluminium or 25mm in steel. With high spatial resolution, neutron diffraction can provide complete three-dimensional strain maps of engineered components. This is achieved through translational and rotational movements of the component.

This method of stress evaluation, with the capacity for collecting large quantities of data (via position sensitive detectors) over the whole surface and depth (depending on the thickness of the sample) has made neutron diffraction a particularly useful technique for the validation of theoretical and numerical models.

However, compared to other diffraction techniques such as X-ray diffraction the relative cost is much higher and the availability very much lower. At the moment neutron diffraction is carried out at central facilities, including ISIS (Didcot), ILL (Grenoble), Saclay (Paris) and Chalk River (Canada). Within Europe beam-time is available under peer review only, and usually the instrument must be booked several months in advance.

Neutron diffraction is being used commercially to optimise new joining processes so as to minimise the development of residual stresses [89], and to assess the role of cementite in carbon containing steels during deformation [90]. Such studies have shown that neutron diffraction can and will be a powerful engineering tool, both now and in the future. Some useful references are included in Refs [89-93].

VAMAS TWA20 (Versailles Project on Advanced Materials and Standards, Technical Working Area 20) is an international initiative led by Professor George Webster of Imperial College. The aims are to carry out basic research that enables the development of an international standard for making residual stress measurements in crystalline materials by neutron diffraction. To this end, the group performed a series of round robin measurements on 4 artefacts including a shrink-fit ring and plug, which is now completed [29]. A Bayesian statistical analysis that was applied to the data indicated no significant differences between measurements made on individual crystallographic planes or when the entire diffraction spectrum was examined.

6.5 Curvature and Layer Removal

The curvature and layer removal techniques are often used for measuring the presence of residual stress in simple testpiece geometries. The methods are generally quick and require only simple calculations to relate the curvature to the residual stresses.

When layers are removed from one side of a flat plate containing residual stresses, the stresses become unbalanced and the plate bends. The curvature depends on the original stress distribution present in the layer that has been removed and on the elastic properties of the remainder of the plate. By carrying out a series of curvature measurements after successive layer removals the distribution of stress in the original plate can then be deduced.

The curvature of the specimen can be measured using a variety of methods including optical microscopy, laser scanning, strain gauges, or profilometry, depending on the resolution and range of the measuring instrument. Measurements are usually made on narrow strips to avoid multiaxial curvature and mechanical instability. This technique has been used successfully for polymeric composites [94], polymeric mouldings [95] and coatings [96-101]. Layer removal is applicable only to plate samples and is suitable for measuring in-bulk macro-stress measurements. Stresses at or very near the surface cannot be measured by this technique.

For coatings, a variation of the technique is often used, whereby the curvature measurement of the substrate is monitored as successive layers of coating are deposited [16]. The method uses the same basic principles as the layer removal technique by measuring changes in curvature to deduce residual stress, but in this case these are due to deposition of the coating.

6.6 Magnetic Methods

Magnetic properties have been utilised for residual stress measurements and their primary advantages are that they are non-destructive, cheap, simple and very rapid.

The ferromagnetic properties of steels and other ferromagnetic materials are sensitive to the internal stress state due to magnetostriction and the consequent magnetoelastic effect [102]. Magnetostriction is the process whereby each magnetic domain is strained along its direction of magnetisation. At minimum energy the magnetisation will align with the crystalline

directions – the magnetic easy axes. A change in the stress level will result in a change in the number of domains aligned along each of the easy axes leading to a reduction in the magneto elastic energy. Although the stress dependence of the magnetic parameters is quite strong, there are many other variable, such as hardness, texture, grain size, etc. which also affect the measurement. For this reason, a combination of magnetic techniques is required so that the effect of these other variables can be eliminated. This is the basis of the AEA Technology MAPS System [3,102], which incorporates a combination of Stress Induced Magnetic Anisotropy (SMA) together with Directional Effective Permeability (DEP) methods into a single instrument.

The method requires calibration of the magnetic parameter against known stress levels, and theoretical formulae are then used to interpolate and extrapolate the calibrations. The primary advantages of the magnetic methods are that they are very rapid (measurements normally made in seconds), the equipment is fully portable and can measure biaxial stresses, typically to a depth of ~6-10mm. The weakness of the magnetic techniques is the limited range of materials which can be examined and the inherent sensitivity to a variety of other microstructural features.

Several variants of magnetic methods are described in the review by Buttle [3] and included in Refs 102-107.

6.7 Ultrasonic Methods

Ultrasonic methods utilise the sensitivities of the velocity of ultrasound waves travelling through a solid to the stress levels within it.

Changes in the speed of ultrasonic waves in a material are directly affected by the magnitude and direction of stresses present. Because the velocity changes are small and are sensitive to the material's texture (grain alignment) it is often more practical to measure transit times as the ultrasonic path length is usually not known to sufficiently high precision [3]. Because the changes in velocity depend on the stress field over the entire ultrasonic path, the spatial resolution is poor. The acoustoelastic coefficients necessary for the analyses are usually calculated from calibration tests. Whilst ultrasonic methods provide a measure of the macro residual stresses over a large volume of material, the presence of texture in the material often restricts their spatial resolution. Nevertheless, they have the advantage of being able to measure in the bulk of the material and are therefore well suited to routine inspection operations. Additionally, the instrumentation is portable and quick to implement. For more details on this technique, see Refs.1,3,108-110.

6.8 Piezo-spectroscopic (Raman)

The Raman effect involves the interaction of light with matter. Incident laser light causes the bonds between atoms to vibrate. Analysis of the scattered light, known as Raman spectrum, reveals vital information about a sample's physical state and chemical structure. This technique is non-destructive and non-invasive and has a high spatial resolution (1 μm or less).

Raman or fluorescence lines shift linearly with variations in hydrostatic stress. This method has fine spatial resolution and by using optical microscopy it is possible to select regions of interest just a few microns in size. The method is essentially a surface strain measurement technique, but with optically transparent materials such as sapphire it is even possible to

obtain sub-surface information. Materials that give Raman spectra include silicon carbide and alumina-zirconia ceramics and the method is particularly useful for studying fibre composites [112,113].

A variation of the Raman method uses fluorescence spectra to enhance the applicability of the technique to a wider range of materials.

6.9 Other Techniques

Many other techniques are being developed for measuring residual stresses most of which are still in the research and development stage. Some papers on the electron back scattered diffraction patterns (EBSP) technique are given in Refs. 114-116.

The reader is also advised to consult the reviews by Withers and Bhadeshia [2] and by Buttle [3] for the current status and developments.

7 RECENT DEVELOPMENTS

There have been significant advances recently in this field, both in the measurement techniques and in modelling and predicting component performance. This is evident from the number of publications in journals and conferences. New standards are now being developed for the XRD and neutron diffraction methods.

7.1 Publications and Conferences

The latest in the *International Conference on Residual Stresses* series, ICRS-6, was held in Oxford, UK, in July 2000 [117]. Over 130 written papers and 60 posters were presented covering almost all aspects in this field, including measurement techniques, research investigations involving one or more of these techniques, standard developments and computer modelling of component behaviour. The proceedings represent a good source of information on the state-of-the-art in this area.

7.2 Measurement Standards

Results from a French inter-laboratory comparison, involving 16 laboratories using 21 different XRD instruments [28], have identified the type of software used for analysing the data and the operator as the two most important parameters contributing to test uncertainty. The inter-laboratory average value of σ_{11} was -469 MPa and the standard deviation was about 36 MPa. A French national standard for residual stress measurement based on the findings in the above-mentioned study is being prepared.

The UK input into *CEN/TC 138*, the technical committee on *Non-destructive Testing*, who are planning to develop a standard for *Measuring Residual Stress using XRD* is being coordinated in the UK by BSI Panel WEE/46/-/18. It is proposed that the *Good Practice Guide* being developed as part of the current DTI-funded activity at NPL should form the basis of the UK contribution.

Japanese standards based on the $\sin^2 \psi$ method have been developed for use with steels and recently extended for ceramic materials [118].

The international investigation under the auspices of VAMAS TWA20 (Versailles Project on Advanced Materials and Standards, Technical Working Area 20) for residual stress measurements in crystalline materials by neutron diffraction is being carried out on 4 articles [29]. Work is in progress towards preparing an international protocol with the aim of publishing it as Technology Trends Assessment (TTA) by ISO in 2001.

8 SUMMARY

Numerous publications have been produced on the subject of residual stress and significant advances have been made recently to improve current measuring techniques. However, a number of important issues still remain including the uncertainties in the measurement, reliability and interpretation of results and, for many techniques, the general lack of standards and reliable techniques.

Within the current DTI-sponsored project at NPL, 2 separate Good Practice Guides for measuring residual stress by the XRD and Hole Drilling will be produced, based on detailed experimental studies and industrial consultation, and these should prove invaluable for improving the quality and reliability of residual stress measurements by these techniques.

Generally, there is still a real need for improving the understanding of the influence of residual stresses on performance. This should be addressed by better education of all those involved in the supply and processing of material to the design team, engineers, production staff and end users to the potential benefits, disadvantages and contributions of residual stress to their success and profitability.

The ability to measure and monitor the development of residual stresses in a component at various stages of manufacture is a key issue.

ACKNOWLEDGEMENTS

This work was carried out in project CPM4.5 on the *Methods of Measuring Residual Stress in Components*, which is part of the CPM programme on *Characterisation and Performance of Materials*, funded by the Engineering Industries Directorate of the UK Department of Trade and Industry.

The authors would like to thank all members of the Industrial Advisory Group who have made comments and contributed to the review.

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