Efficient use of available techniques to measure residual stresses in welded components.

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ABSTRACT

As the design of engineering components becomes less conservative, there is an increasing interest in how residual stresses affect mechanical properties and how to estimate them practically. Experimental measurements are essential to establish a quantitative understanding of the sign, magnitude and distribution of the residual stresses around the weld, within acceptable limits.

There are many methods for characterization of residual stresses in engineering components. Measurements of residual stress can be very expensive and time consuming. Before selecting one method over another, it is important to consider the advantages and limitations of those techniques to optimize the benefits of the investigation.

In this paper, destructive, semi-destructive and non-destructive techniques are reviewed. The focus is on the application of these techniques to the quantitative measurements of residual stress in the welded components.

1 Introduction

Residual stresses can be defined as those stresses that remain in a material or body after manufacturing and processing in the absence of external forces and thermal gradients. They are sometimes referred to as internal stresses, or locked-in stresses. These internal stresses are balanced within the component. If the tensile and compressive residual stresses are unbalanced, the body will deform to restore equilibrium.

It must be kept in mind that residual stresses are three-dimensional and can occur in a component on both a macroscopic and microscopic level [1,2]. Three kinds of residual stresses are defined based on their scale: macrostresses, σ^{I}, (or stresses of the first kind) which act on the area of a few grains; the stresses of the second kind, σ^{II}, that act over one particular grain; and stresses of the third kind, σ^{III}, that act across sub-microscopic areas, say several atomic distances within a grain. Stresses of the second and third kinds are also called microstresses. Microstresses can be treated as scalar properties of the sample, such as percent of cold work or hardness, which are without direction and result from imperfections in the crystal lattice. Macroscopic stresses which extend over distances that are large relative to grain size of the material are of general interest in design and failure analysis. Of special practical interest are the macrostresses, or stresses of the first kind, as they are significant contributors in the design and analysis of structures.

In particular, in welded structures residual stresses are formed primarily as the result of differential contractions which occur as the weld metal solidifies and cools to ambient temperature. A weldment is heated locally in the welding process; the temperature distribution in the weldment is not uniform and changes as the welding progresses. The temperature and temperature distributions affect expansion and contraction and the relationship between stress and strain and thus, residual stresses [3,4].

Over the last few decades, various quantitative and qualitative methods for measuring residual stresses have been developed. However, residual stress (RS) cannot be measured directly. It is derived from residual strain measurements. Additionally, no measurement technique can measure the residual strain at a single point in a component. Various techniques measure a strain averaged over a sampled gauge volume.

2 Residual stress measurement techniques

There are various ways of measuring residual stresses such as destructive, semi-destructive and non-destructive techniques, which will be explained in more details in the following sections.

2.1 Destructive techniques

Destructive methods of RS measurement are fundamentally stress relaxation procedures. The first series of methods is based on destruction of the state of equilibrium of the RS after sectioning of the component, machining or layer removal.

2.1.1 Slitting

The redistribution of the internal forces leads to local strains which are measured to evaluate the RS field. RS is deduced from the measured strain using linear elasticity theory (analytical approach or finite element calculations). The slitting technique (ST) is only sensitive to the macroscopic RS (Type I). Residual stresses can result in visible distortion of a component. The distortion can be useful in estimating the magnitude or direction of the residual stresses [1,5]. These simple and cheap techniques, sometimes known as dissection, are old but still very useful. However, as described by Walton [6], slitting a component is a destructive method and there are the limitations, particularly if the component in question is large and complex.

2.1.2 Contour method

The contour method (CM) is a relatively new stress relaxation method which enables two-dimensional contour stress maps to be obtained. The process is not a layer by layer removal process, but rather a single cut is made along the specimen plane of interest. The theory is based on the variation of Bueckner's elastic superposition as shown in detail by Prime [7]. A specimen is parted in two using electric discharge machine wire cutting causing the residual stresses to relax. A detailed contour profile map is taken from the cut plane measuring the displacement due to stress relaxation using a co-ordinate measuring device. Using finite element analysis, a three-dimensional model of the cut section is constructed. The exact opposite contour profile measured is then applied to the surface as a displacement boundary condition. The RS distribution normal to the cut plane is then obtained.

This technique can be applied in many applications and to relatively complex geometries. Results have been shown to correlate reasonably well with other measurement techniques such as neutron diffraction and numerical modelling [8,9].

2.2 Semi-destructive techniques

Semi-destructive techniques (e.g., hole-drilling and trepanning) have a small to negligible effect on the components in which the stresses are measured, or the area of the investigation may be repaired after the measurements.

2.2.1 Hole drilling technique

The hole-drilling (HD) strain-gauge technique measures the RS near the surface of isotropic, linear-elastic materials. The method is described in detail in ASTM E 837-99 [10].

The test method is often described as "semi-destructive" because the damage that it causes is localized and in many cases does not significantly affect the usefulness of the specimen. The hole-drilling method involves the application of a special three-element, strain-gauge rosette on to the surface of the component at the measurement location. A small hole (approximately 1-2 mm diameter) is then made into the component through the centre of the rosette. The production of the hole in the stressed component causes a redistribution of strains to occur near the hole which can be detected and measured by the surface-mounted, strain-gauge rosette. The measured relieved strains due to the hole production can be related to the original surface RS.

Nevertheless, if the RS exceeds about 50% of the yield stress then errors can arise due to localized yielding (see ASTM E 837-1999 [11]). Although it is possible to deduce the variation in the stress with depth by incrementally deepening the hole, it is difficult to obtain reliable measurements much beyond a depth equal to the hole diameter. There are many factors that can influence the error sensitivity of the measurements, like hole depth, hole diameter, and material properties estimation. In particular, nonuniform stress measurements are much more sensitive to measurement error than uniform stress evaluations. This error sensitivity occurs because the strains are measured at the specimen surface, whereas the desired nonuniform stress is deep in the interior.

Nevertheless, the method is popular and economical and widely used. Recent advances have been made in methods to increase the reliability of the measurements [7,11]. One such example described by Schajer and Tootoonian [12] involves using a six-element, strain-gauge rosette to greatly improve the RS measurement accuracy. Experimental measurements using this technique agree with theoretical strain response calculations within 3-4 percent.

2.2.2 The ring-core (trepan) technique

The ring-core (trepan) technique (TT) is a mechanical, strain-gauge technique employed to describe the principal RS field as a function of depth in polycrystalline or amorphous materials. The method is based on the same principles as the hole drilling technique, and also involves placing a strain-gauge rosette on the surface at the location of interest on a given component. An annular groove is machined around the strain-gauge rosette at predetermined depth increments. The strain relaxation which occurs as a function of machined depth is recorded. The final RS values are calculated using the measured change in strain values with depth of the ring [1,5,13].

The ring-core method works well on materials which are coarse grained, such as cast metals or weldments. It can be used on ceramics and plastics as well as metallic materials. The method is valid for RSes up to 100% of yield strength. However, the disadvantages of this method include low sensitivity to placement of the strain gauge, eccentricity of the machined ring and low sensitivity to near-surface stresses.

In conclusion, mechanical methods are limited by assumptions concerning the nature of the RS field and geometry. Mechanical methods, being necessarily destructive, cannot be directly checked by repeated measurements.

2.2.3 Deep hole drilling technique

Procedures are currently in development to extend the measurement depth in thick sections of engineering components. The deep hole drilling (DHD) technique has been developed for measuring RS in thick sections. It involves drilling a reference hole through the specimen. The drilled diameter is accurately measured along its depth. A trepanning technique is then used to remove the column containing the centre reference hole causing the RS to relax. The change in the reference hole diameter and column dimension are used to calculate residual stresses.

This technique has been used to measure a thick section of a complex shape. The developments of the DHD technique and comparison of the measurements with finite elements method are reported by Leggatt et al. [14], George et al. [15] and George and Smith [16]. It is shown by Andersen [17] that the deep-hole method can measure linear and non-linear stress distributions.

2.3 Non-destructive diffraction techniques

Diffraction techniques are based on the use of the lattice spacing as a strain gauge. It allows the study and separation of the three kinds of RS. They are one of the most efficient non-destructive techniques.

Diffraction measurements provide much more information than conventional strain gauge techniques. The well–defined subset of grains in the sampling gauge volume producing each diffraction peak provides insight about micro and macrostrains within the sample.

Diffraction techniques exploit the crystalline lattice of the material as an atomic strain gauge as shown in Figure 1. When a beam is passed through a polycrystalline material, diffraction occurs according to Bragg's law which is given by the equation:

$$n\lambda = 2d_i \sin\theta_i \qquad (1)$$

where *n* is any integer and θ_i is the Bragg angle for a crystallographic plane, *i*, having interplanar spacing, d_i.

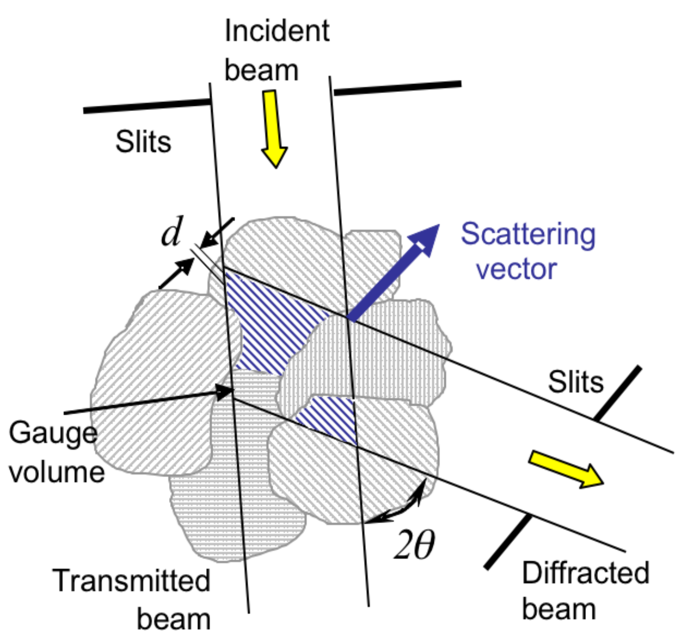

Figure 1. Principles of the diffraction technique showing Bragg reflection from the crystal plane *d*. (Grain size is greatly exaggerated for clarity.)

Under an applied tensile (or compressive) stress, the lattice spacing (d_i) in individual crystallite grains expands (or contracts). This change in the lattice spacing can be detected, at a constant wavelength, as a shift ($\Delta\theta_i$) in the diffraction peak, from the Bragg equation (1).

2.3.1 Laboratory X-ray diffraction

X-ray diffraction (XRD) has been used extensively in many scientific and engineering fields over the years [18]. Since X-ray diffraction is only able to probe a very thin surface layer, due to the low energy of the X- rays (<10 keV), the method is primarily applied to surface measurements. However, information on RS distributions can be obtained at greater depths (up to about 1 mm) by successively removing material (usually by electropolishing) [19].

It is assumed in stress determination, that the stress normal to the free surface is zero, which reduces the system to two principal stress components lying within the plane of the sample surface. The conventional $\sin^2\psi$ method is applied [20].

Using this method it is possible to evaluate the in-plane stress by measuring the *d*-spacing at a series of angles, without the necessity of comparing with a stress-free reference d_o. This is a major advantage of the $\sin^2\psi$ method. With the assumption that the stress in the normal direction (z) to the surface is equal to zero, the bi-axial stress components, transverse (x) and longitudinal (y), are measured on the surface. Results obtained by X-rays are affected by the presence of an inhomogeneous stress/strain state within material [1,5]. Portable X-ray equipment is now available. The advantage of this technique and a comparison with the hole drilling technique is described by Lord et al. [21]. There have been several studies published recently using this technique to evaluate residual stresses in welded structures [22].

2.3.2 Synchrotron X-ray diffraction

Many of the limitations of the laboratory X-ray techniques have been overcome by the introduction of third generation synchrotron sources [20].

The penetration and flux available from synchrotron X-ray strain measurements lead to an elongated, diamond-shaped gauge volume with an aspect ratio typically of about 10:1. The low divergence allows measurement of lattice plane spacing, *d*, with high spatial resolution within a sample.

Withers [1] reported that very few studies have been undertaken using synchrotron diffraction (SD) so that the engineering potential of the technique is still largely untapped. It is anticipated that the development of synchrotron strain scanning will fill the important near-surface gap between what is possible with neutrons and what is accessible with traditional X-ray techniques. Synchrotron X-ray diffraction [23,24,25,26] is very well suited to the measurement of strain in the near-surface region and in most cases 2D strain maps are produced. This technique has been successively applied to measure the strains in welded components [27, 28, 29]. The work was carried out by experimentalists [28,30,31] to help develop and validate the finite-element model of RS distribution.

2.3.3 Neutron diffraction

Neutron diffraction (ND) is a measurement technique which closely parallels X-ray diffraction in methodology and analytical formalism. However, because neutrons interact with nuclei and X-rays with electrons, neutrons are typically about a thousand times more penetrating than X-rays. Therefore neutron diffraction is outstanding in its ability to obtain residual stresses non-destructively within the interior of components, in three dimensions, in small test volumes (down to 0.5x0.5x1 mm^3) and in thick specimens (up to several cm).

An international standard ISO/TS 21432-2005 [32] for measuring residual stresses using ND is being developed on a ring-plug fit to achieve reproducible and reliable stress measurements.

The precision of strain measurements using these techniques relies on having adequate diffraction peak intensity, which involves important underlying issues, such as controlling beam path, taking account of absorption in the sample, material grain size, and background scattering [1,5,29]. Additionally, a gauge volume which determines the resolution of the experiment is often optimized to be the smaller than the changes in the RS states which need to be measured and at the same time as large as possible to enable sufficient measurements in the allocated beam time [29]. Furthermore, to gain an appreciation of the absolute stresses involved, measurement of a stress-free reference sample is probably the most critical part of any ND experiment, particularly for welded components. It is recommended as good experimental practice to manufacture the cubes from the weld and parent metal or a comb specimen across the whole weld if possible, to demonstrate issues related to the grain size and other material variations [29].

Nevertheless, ND has been successfully applied to establish RS distributions in aluminium alloys for fusion [30] and friction [34,33] processes, as well as for ferritic [9,29,34,35,36,37] and stainless [38,39] steel welds. Elcoate et al. [40] showed reasonable agreement between deep-hole drilling, numerical modelling and neutron diffraction on a multi-pass welded pipe. The authors' own work has shown there are limitations to the agreement which can be achieved due to issues of gauge volume in both the experimental work and the theoretical work [41]

3 Comparison of techniques

Based on the literature review, a comparison of the physical characteristics of the techniques discussed in the previous sections is shown in Table 1. The comparison of spatial resolution versus penetration for steel welded components is shown on Figure 2.The limitations and other practical issues that have to be taken into account are shown in Table 2. The advantages and disadvantages of these techniques are shown in Table 3.

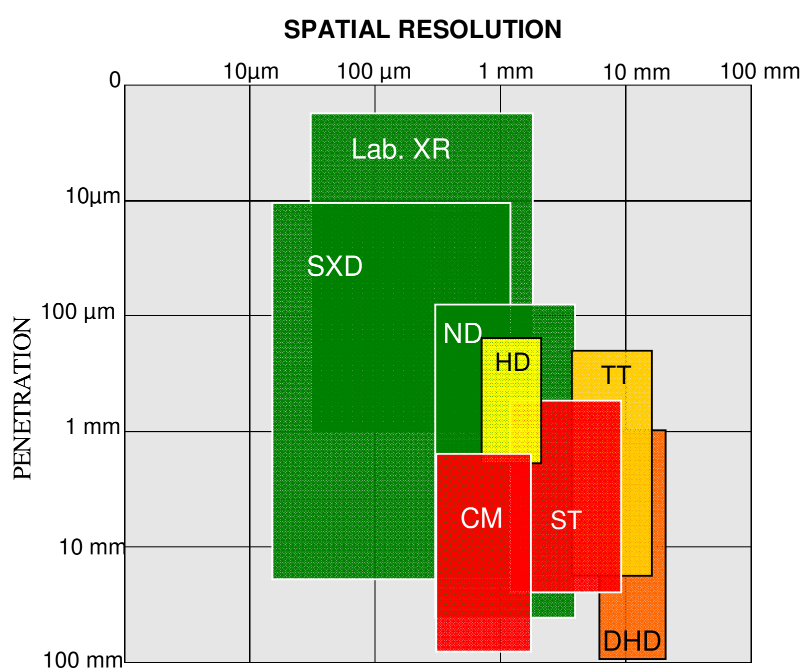

Figure 2. Comparison of RS spatial resolution versus penetration for steel components.

Table 1. Comparison of the physical issues of RS measurement techniques applied to welded components

Key techniques	Resolution	Max. penetration	Sampling area/ Volume	Stress type	Stress state	Stress gradient	Accuracy	Remarks
Slitting (distortion as stresses arise or relax)	Couple of mm	No t applicable	No t applicable s	Macro	Uniaxial	No	5-10% of the yield stress of the material	Limited to the simple components
Contour Method (distortion caused by stress relaxation on the surface of the cut)	Dependent on material & measurement s method	Limited to the precision of cutting trough thick section	2D map of the distribution	Macro	Uniaxial	Yes	±50 MPa	Sensitive to the precision of cutting. Limited by minimum measurable distortion
Deep Hole drilling(distortion caused by stress relaxation)	Ring diameter (5-20 mm) and depth increment	100 mm– Al 100 mm – Fe	5-20 mm diam. 0.5-2 mm deep	Macro	Uniaxial Biaxial	Yes	±30-50 MPa Varies with depth	Able to measure a thick section of a complex shape, but limited to few locations
Hole Drilling (distortion caused by stress relaxation)	hole diameter (1-2mm) and depth increment (50-100 μm)	Hole depth (1-2mm)	1-2 mm diam. 1-2 mm deep	Macro	Uniaxial Biaxial	Yes – difficult to interpret	±50 MPa Varies with depth	Sensitive to surface preparation drilling technique and strain measurements through the thickness
X-Ray Diffraction (atomic strain gauge)	20 C depth 1mm laterally	20 μm – Fe 50 μm – Al	0.1-1 mm^2 0.05-0.1 mm	Macro Micro	Uniaxial Biaxial	Yes with layer removal	±20 MPa Limited by non-linearity in $sin^2\psi$	Sensitive to surface preparation and texture
Synchrotron Diffraction (atomic strain gauge)	20 μm lateral incident beam , 1 mm parallel	100 mm– Al 20 mm – Fe	>0.2 mm^3	Macro Micro	Uniaxial Biaxial Triaxial	Yes	±10 $x10^6$ strain Limited by grain sampling Reliability of ref. sample.	Low scattering angle, this leads to gauge volume having elongated diamond shape.
Neutron Diffraction (atomic strain gauge)	From 500 μm to 4mm depending on the thickness	100 mm – Al 50 mm – Fe 8 mm - Ti	>1 mm^3	Macro Micro	Uniaxial Biaxial Triaxial	Yes	±50 $x10^6$ strain Limited by number of counts Reliability of ref. sample	Not suitable for surface measurements because of the shifts in the centre of gravity of the diffracting volume when it is only partially filled.

Table 2. Comparison of the practical issues of RS measurement techniques applied to welded components

Key techniques	Size of component	Contact or non contact	Destructive	Lab based or portable	Availability of equipment	Speed	Standards available	Cost of equipment	Level of expertise
Slitting	Small, medium and large	Contact	Yes	Both	Generally available	Med	No	Low	Low
Contour Method	Small, medium and large	Contact	Yes	Lab.	Available	Med	No	Low/ Med	Med/High
Deep Hole Drilling	Medium and large	Contact	Yes or semi	Both	Available	Med	No	Low/ Med	Med/High
Hole Drilling	Small, medium and large	Contact	Yes or semi	Both	Widespread	Fast/ Med	ASTME 837-99 [10]	Low/ Med	Low/ Med
X Ray Diffraction	Small, medium and large	Non-contact	No	Both	Generally available	Fast/ Med	No	Med	Low/ Med
Synchrotron Diffraction	Small and medium.	Non-contact	No	Lab.	Specialist	Fast	No	Strategic Government facility	High
Neutron Diffraction	Small, medium and large	Non-contact	No	Lab.	Specialist	Med/ Slow	ISO/TTA3 : 2001[32]	Strategic/ Government facility	High

Table 3. Advantages and disadvantages of RS measurement techniques

Techniques	Advantages	Disadvantages
Slitting (ST)	• Relatively simple • Wide range of materials • Can be combined with other techniques to give stress profile	• Destructive • Limited to simple shapes
Contour Method (CM)	• Suitable for thick section components • 2D maps of RS in uniaxial direction measurements	• Destructive • Lab-based • Limited to symmetric distribution of stress
Deep Hole Drilling (DHD)	• Might be portable • Suitable for very thick section components • Biaxial measurements of RS	• Destructive or semi-destructive • Measurements limited to few locations
Hole Drilling (HD) and Trepanning Technique (TT)	• Quick, simple • Widely available • Portable • Biaxial measurements of RS	• Interpretation of data • Semi-destructive • Limited strain sensitivity and resolution
X Ray Diffraction (XRD)	• Non-destructive and stress gradient measurements • Versatile, widely available • Wide range of materials • Portable • No stress-free reference sample needed • Biaxial measurements	• Basic measurements • Surface measurements only • Most of the time electropolishing required
Synchrotron Diffraction (SD)	• Non-destructive and stress gradient measurements • Improved penetration & resolution of X-rays • Depth profiling • Very fast 2D strain maps • Biaxial measurements	• Specific facility only • High cost. • Lab-based • Reference stress free sample required
Neutron Diffraction (ND)	• Non-destructive and stress gradient measurements • Excellent penetration & resolution • Suitable for thick section components • Triaxial measurements	• Specific facility only • High cost. • Lab-based • Reference stress free sample required

4 Conclusion

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

Measurements of RS can be very expensive and time consuming. Before selecting one method over another, it is important to consider the sampling volume characteristic of the technique and the type of stress, which may be important.

In many cases, much can be learned from the complementary use of more than one technique. For instance, diffraction techniques, on account of the differences in absorption and penetration of the beam, are not competitive but complementary to each other.

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