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Current and Challenge of Residual Stress Measurement Techniques

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Abstract: *Compressive residual stresses which prolong fatigue life and decrease the speed of initiation of crack, are desirable. Choosing a method for measuring the residual stress depends on many factors. To this regards some of the residual stresses measuring techniques, that divided into destructive and non-destructives methods, were reviewed in this study. For destructive techniques, hole drilling is the most method used due to well-established, cheap and simplicity of this method. For non-destructives techniques X-ray diffraction is the most used technique, due to versatile, widely available, wide range of materials and macro and micro residual stress measuring. All residual stress measurement techniques did not measure the stress directly; the stress was calculated after measuring the strain.*

Keywords: Residual Stress, Hole drilling, X-ray diffraction, Laser Shearography, residual stress relaxation.

1. Introduction

Residual stresses are those stresses existing along a cross-section of a component without applied external forces [1], residual stresses can by categorized in three types in accordance to their extensions; (1) type I; these stresses vary within the body of the component over a range much larger than the grain size and may cover an area of several material's grains, (2) type II which extends over a distance of one grain or a part of it and (3) type III which appear in small portion of the material and vary within several atomic distances in the grain limits [2-5]. Type I called macro residual stress while type II and III are called micro residual.

In almost every step of material processing residual stresses can be arise due to: (1) mechanical affects; which generate residual stresses by producing plastic deformation as a result of processes during production or treatment, however the residuals tress can be introduced mechanically into a component to develop a particular stress profile, (2) thermal affects; residual stress can be generated as a result of heating or cooling processes these processes combined with the material limitation can direct to develop internal stresses due to severe thermal gradients, and (3) chemical affects; reaction such as precipitation can generate residual stress in a component due to volume change. Chemical surface treatment, coating and nitriding can also generate residual stresses [6].

Residual stresses can be desirable or undesirable. Residual stresses in a surface of a component can be either a tensile residual stress or a compressive residual stress. In particular, near surface tensile residual stresses tend to accelerate the initiation and growth phases of the fatigue process while compressive residual stresses close to a surface may prolong fatigue life [7]. For plastically deformable materials, the residual and applied stresses can only be added together directly until the yield strength is reached. In this respect, tensile residual stresses may accelerate the onset of plastic deformation, while compressive residual stress delay it. Residual stress can raise or lower the mean stress experienced over a fatigue cycle [7, 8].

Mostly, surface tensile residual stresses are undesirable. Welding, machining and grinding are examples of operations that generate surface tensile stresses [7]. Tensile residual stresses may decrease the performance or cause failure of manufactured products. They may increase the rate of damage by fatigue, creep or environmental degradation. They may reduce the load capacity by contributing to failure by brittle fracture, or cause other forms of damage such as shape change or fine crack on the surface [7]. One of the most significant causes of residual stresses is welding that creates a magnitude of tensile stresses equal in value to the material yield strength, a compressive residual stresses balanced these tensile stresses in another place in the component. Minimizing tensile residual stresses in welded components can be done by appropriate selection of: welding process and parameters suitable for the welded material, fabrication sequence and structural geometry. Moreover, various special welding techniques can reduce tensile residual stresses this including low stress non-distortion welding, last pass heat sink welding or inter-run peening. However, if it is not applied properly the residual stresses may be increased [9]. In addition to this some processes to relief tensile residual stresses are existing to introduce beneficial compressive residual stresses, such as low plasticity burnishing (LPB) and shot peening [9].

Introducing near surface compressive residual stresses leads to improve in component performance which is desired. Compressive residual stress can be generated by surface plastic deformation and usually considered as major factor in increasing fatigue life and received more attention in research [6, 8, 10].

The evaluation of existing residual stress states still today is often not clear. The reason is that quite a number of specific aspects have to be taken into account in measuring residual stresses making such analyses sometimes difficult and doubtful. In general, the statement that residual stresses have a positive or detrimental effect on the behavior of technical parts or components is valid. Mostly, the ignorance of existing residual stress states and their significances is used to explain unexpected failure.

In this study, a review of the residual stresses measurements techniques was done. The measurement techniques were divided into destructive and non-destructive. An attention to the most used technique in each category was paid, particularly to hole drilling and X-ray diffraction. It is worth noting that in residual stress measurements, stress is not measured directly by the measurement methods; it is always strain that is measured. Then the stress is calculated using appropriate equations.

2. Residual Stress Measurement Techniques

The techniques used to measure residual stress can be divided generally into two types:

- Destructives such as curvature, hole drilling, compliance methods
- Non destructives such as magnetic and electrical, utrasonic, thermoelastic, photoelastic and diffraction methods

2.1 Destructive methods

Destructive methods are the methods that destroy the sample to relief the stress.

2.1.1 Curvature Method

Curvature measurements are frequently used to determine the stresses within coatings and layers. The deposition of a layer can induce stresses which cause the substrate to curve [11] as illustrated in Fig. 1. The resulting changes in curvature during deposition make it possible to calculate the corresponding variations in stress as a function of deposit thickness. Curvature can be measured using contact methods (e.g. profilometry, strain gauges) or without direct contact (e.g. video, laser scanning, grids, double crystal diffraction topology) [12], allowing curvatures down to about 0.1 /mm to be routinely characterized.

Measurements are usually made on narrow strips (width/ length ≤ 0.2) to avoid multi-axial curvature and mechanical instability.

The Stoney [13] equation is often used to relate the deflection g of a thin beam of length l and stiffness E to the stress σ along the beam

$$\sigma = -\frac{Eh^2}{3l^2}\frac{dg}{dh} \quad (1)$$

where, h is the current thickness.

This has been done for metallic and polymeric composites and for thin coatings produced using plasma or chemical vapour deposition [14] and physical vapour deposition [12]. When incremental layer removal is impractical, it is possible to estimate the in-plane stress levels if assumptions are made about their through thickness distribution. There is some ambiguity in this latter approach, because the stress distribution associated with a given curvature is not unique.

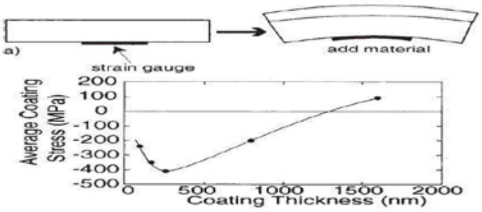

Figure 1: basis of method for monitoring development of residual stresses during deposition, experimental data were obtained for various thickness of sputtered [9]

2.1.2 Crack Compliance Methods

The crack compliance method is basically cutting a small slot to see the relaxation of stress in the vicinity of the crack using strain gauge interferometry. Increasing the depth of the slot will allow resolving the stress field normal to the crack as a function of depth for relatively simple stress distributions [15].

Various removal techniques have been reported. For example, it has also been possible to monitor residual thermal stresses in the fiber phase of a continuous fiber metal matrix composite by etching away the matrix and measuring the change in the fibre length. Another method is based on cutting a section by electro discharge machining and inferring the prior normal stresses from the deviations from planarity [16].

2.1.3 Hole Drilling

The hole drilling method is one of the most widely used techniques for measuring residual stress. The procedure involves drilling a small hole into a specimen containing residual stresses. The relieved surface strains can be measured by a special residual stress strain gauge rosette, allowing a back-calculation of residual stress to be made [17]. Relaxation of residual stresses at the hole boundary results in changes in strain gauge output. The basis of the hole drilling to determine the residual stress is that when material is removed from a surface under stress, it allows the surface to relax slightly and therefore it relaxes the residual stresses. The undisturbed regions of a sample containing residual stresses will relax into a different shape when the locality is machined, thereby providing data for the back-calculation of residual stress [17].

The assumptions made in the hole drilling method for measuring residual stresses are that the materials is isotropic, linear elastic and that the variations of stress within the boundaries of the hole are small [18].

The advantages of hole drilling method is that this method can be used on large components and in situ as the equipment is portable. The actual test is quick and inexpensive and can be done on a wide range of materials with curved or flat surfaces [18].

Strain gauges measure strain by use of many small wires. The resistance of these wires changes as the length is altered. So if the gauge is fixed to a surface, the change in resistance of the gauge will be an indication of the change in strain of the surface. The gauges should be arranged in a circle around the hole which will be drilled. The gauge circle and the hole must be concentric. This is done using special alignment gauges and equipment. Good surface preparation and a good quality installation are required to achieve accuracy of measurements [17].

The machining operation usually involves drilling a hole using Hole drilling apparatus (Fig. 2) around which the strain is measured using either a rosette of strain gauges, moire interferometry, laser interferometry based on a rosette of indentations, or holography. In general terms

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

where$\bar{A}$ and $\bar{B}$ are hole drilling constants, and b is the angle from the x axis to the direction of maximum principal stress, $\sigma_{\max}$. For the case of hole drilled in an infinite plate, $\bar{A}$ and $\bar{B}$ must be calculated numerically [19].

Although it is possible to figure out the variation in stress with depth by incrementally deepening the hole, it is difficult to obtain reliable measurements much beyond a depth equal to the diameter. With a three strain gauge rosette it is only possible to measure the two in-plane components of the stress field. Nevertheless, the method is cheap, widely used and it has been applied even to polymeric samples [20].

Water jets have been used in preference to mechanical drilling to reduce the depth of machining induced deformation. If the residual stresses exceed about 50% of the yield stress, then errors can arise due to localized yielding. While the method has been used to assess the levels of stress in coatings [21], it is not really practical for thin (< 100μm) or for brittle coatings.

The limitation of the hole drilling method is that the relieved strains decay rapidly with depth into the metal so the detection is only sensitive to near surface stresses and is variable with depth. Also this method is susceptible to errors in hole position, depth (measured and controlled to within 1 μm [18], diameter and concentricity (must be within ± 0.025 mm [17]). The drilling process can induce stresses and to minimize this high speed drilling is used. The process is destructive and the results are difficult to interpret [18]. Errors may be introduced by the surface roughness and flatness.

The hole drilling process along with the use of calibration coefficients and data analysis is described in ASTM: E837-95 "Standard Test Method for Determining Residual Stresses by the Hole-Drilling Strain-Gauge Method".

Figure 2: Hole drilling apparatus [17]

2.2 Non-destructive Techniques

2.2.1 Magnetic

There are two magnetic methods: the magnetostriction and the Barkhausen noise. The magnetostriction method based on the measurement of permeability and magnetic induction, the Barkhausen noise on the analysis of magnetic domain wall motion [22]. If magnetostrictive materials are stressed the preferred domain orientations are altered. This makes domains most nearly oriented to a tensile stress to grow (positive magnetostriction) or shrink (negative magnetostriction). Stress induced magnetic anisotropy causes the rotation of an induced magnetic field away from the applied direction. It is possible to monitor these small rotations in the plane of the component surface by a sensor coil. If there is no rotation, then the principal axes of the magnetic field and stress are parallel. When the assembly is rotated, both the principal stress directions and the size of the principal stress difference can be measured. Magnetoacoustic emission is the generation of elastic waves caused by changes in magnetostrictive strain during the movement of magnetic domain walls and is generally detected from the material bulk[22]. Barkhausen emission on the other hand, is recorded as a change in the emf proportional to the rate of change in magnetic moment detected in probe coils as domain walls move. It is attenuated at high frequencies by eddy current shielding and so provides only a near surface probe (<250 μm). Magnetic methods have the advantage of providing cheap and portable methods for non-destructive residual stress measurement [15].

Eddy current techniques can simply be described as inducing eddy currents in the material under test and detecting changes in the electrical conductivity or magnetic permeability through changes in the test coil impedance. The depth of penetration can be changed by altering the excitation frequency, but is around 1 mm at practical frequencies, and the probe cannot identify the direction of the applied stress. Recent studies on this method showed that eddy current methods can be applied to a wider range of materials than magnetic methods. Although eddy current methods are not well suited to basic measurements of residual stress due to the sensitivity of eddy current monitoring to plastic work and microstructural changes, they can provide a quick and cheap inspection method [15].

2.2.2 Ultrasonic methods

Changes in ultrasonic speed can be observed when a material is subjected to a stress, the changes providing a measure of the stress averaged along the wave path. The acoustoelastic coefficients necessary for the analysis are usually calculated using calibration tests. Different types of wave can be employed but the commonly used technique is the critically refracted longitudinal wave method. The greatest sensitivity is obtained when the wave propagates in the same direction as the stress [16]. The basic equation for the stress calculation is as follows

$V = V_0 + K\sigma$ (3)

Where, $V_0$the velocity of a wave is in an unstressed medium, σ is the stress and K is a material parameter known as acoustoelastic constant [15].

2.2.3 Diffraction methods

Changes in interplanar spacing d can be used with the Bragg's equation to detect elastic strain ε through knowledge of the incident wavelength λ and the change in the Bragg scattering angle $\Delta\theta$

$\lambda = 2d sin\theta$ (4)

Giving

$\epsilon = {}^{\Delta d}/_{d_0} = -\Delta cot\theta_0$ (5)

It is, of course, usually necessary to have an accurate measure of d_0, the stress free spacing. The strain results can then be converted into stress using a suitable value of the stiffness [17].

2.2.3.1 Neutron diffraction

Neutron diffraction is a non-destructive method of determination of residual stresses in crystalline materials. Neutron diffraction provides the values of elastic strain components parallel to the scattering vector which can be converted to stress. Neutron diffraction measures strain components from changes in crystal lattice spacing. When crystalline materials exposed to radiation of wavelength close to interplanar spacing (0.5-3 Å) elastically and coherently scatter this radiation as distinctive Bragg peaks imaged usually by a position sensitive detector. The angle at which any given peak occurs can be calculated using Bragg's equation [23].

$2d_{hkl} sin\theta_{hkl} = \lambda$ (6)

where $\lambda$is the wavelength of the radiation, d_{hkl} is the lattice plane spacing of a family of crystallographic planes hkl responsible for the Bragg peak and θ_{hkl} is the angular position of this diffraction peak. The peak will be observed at an angle of $2\theta_{hkl}$ from the incident beam. If a specimen is elastically strained, the lattice spacing changes, therefore any elastic strain will be apparent as a shift in the value of $2\theta_{hkl}$ for a particular reflecting plane illuminated by a fixed wavelength. By differentiating the Bragg's equation [23],

$\Delta\theta_{hkl} = -\left({}^{\Delta d}/_{d_0}\right) tan\theta_0$ (7)

where$\Delta d$is the change of lattice spacing, and d_0, the lattice spacing of a stress-free sample of the material. So, the strain in the hkl set of planes can be calculated with

$\epsilon = {}^{\Delta d}/_{d_0} = -\Delta cot\theta_0$ (8)

The direction in which strain is measured is along the scattering vector and is perpendicular to the diffracting planes [18, 19].

2.2.3.2 Synchrotron diffraction

Synchrotrons (hard X-rays), provide very intense beams of high energy X-rays. These X-rays have higher depth penetration than conventional X-rays (~50 mm in Al). This increased penetration depth means that synchrotron diffraction is capable of providing high spatial resolution, three-dimensional maps of the strain distribution to millimeter depths in engineered components. Higher penetration depth is considered as one of the major advantages of synchrotron diffraction over the conventional X-ray diffraction [20].

Another advantage is that intense narrow beams of 1 mm-l0 μm in size are possible. This leads to spatial resolutions that are limited by the crystallite size within the sample not by the instrument. The measurement is also much quicker than the conventional X-ray diffraction. Today synchrotron diffraction is only available at some central facilities, in much the same way as with neutron diffraction [20, 21].

2.2.3.3 Laboratory X-ray diffraction

In Fig. 3 the orthogonal coordinate systems used to derive equations are shown. The axes $\underline{S}_1$ Si are for the surface of the sample with $\underline{S}_1$ and $\underline{S}_2$ on the surface. $\underline{L}_1$define the laboratory system with $\underline{L}_1$ is in the direction of the normal to the planes (hkl) whose interplanar spacing d will be measured. $\underline{L}_2$makes an angle φ with $\underline{S}_2$ and is in the plane which is defined by $\underline{S}_1$ and $\underline{S}_2$. When the interplanar lattice spacing d is obtained from the diffraction peak for a given reflection hkl, the strain component along $\underline{L}_3$ can be obtained using the formula [23]

$(\varepsilon'_{33})_{\phi\psi} = \frac{d_{\phi\psi}-d_0}{d_0}$ (9)

where$d_0$is the unstressed interplanar spacing.

(Primed components refer to laboratory system $\underline{L}_1$ whereas unprimed components refer to the sample coordinate system,$\underline{S}_1$)
The strain in equation 9 can be transformed to the sample coordinate system using tensor transformation [24]

$$(\varepsilon'_{33})_{\phi\psi} = \frac{d_{\phi\psi}-d_0}{d_0} = \varepsilon_{11}\cos^2\phi\sin^2\psi + \varepsilon_{12}\sin2\phi\sin^2\psi + \varepsilon_{22}\sin^2\psi\sin^2\phi + \varepsilon_{33}\cos^2\psi + \varepsilon_{13}\cos\phi\sin\psi + \varepsilon_{23}\sin\phi\sin2\psi \quad (10)$$

Equation 10 is the fundamental equation that is used in x-ray diffraction strain measurement.

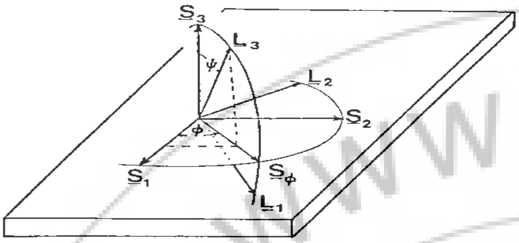

Figure 3: Sample and laboratory coordinate systems [18]

3. Discussions

Residual stresses measurements techniques, as all other tests, are not perfect and imperfections give rise to errors of measurements in the result and uncertainty statement is required [25]. Accordingly, the residual stresses measurements techniques have uncertainty. In this study only the uncertainty of hole drilling and X-ray diffraction will be discussed, this is due to that these two methods are used by 75% of the residual stresses measuring companies and academics [26].

3.1 XRD sources of Errors

One of the most uncertainties of XRD is measuring of un-stressed d-space. There are various ways to determine the unstressed lattice spacing d_0 . Based on the biaxial assumption, the lattice spacing measured at $\psi = 0$ is substituted for d_0 due to the fact that this assumption introduces a negligible amount of error. Another method uses the data obtained during stress measurement itself. If the stress state is biaxial, this method can be used to determine d_0 from the d vs. $\sin^2\psi$ graph. The methods for determining the unstressed d-space is affecting the accuracy of the measurements. Increasing of d_0 will reduce the amplitude of the measured residual stress [27].

In addition to the factors mentioned above, a number of parameters can contribute to the introduction of the error in the measurements, such as the number of Psi angles for $\sin2\psi$ technique, peak position method, plane curvature, aperture dimension and fluctuation. However, The X-ray diffraction is one of the best developed methods available for residual stress determination. There are many improvements of the hard and soft ware of the XRD equipments as well as calculation correction factors to increase the measuring accuracy of XRD. The accuracy of residual stress measurement of XRD method is ±20 MPa, limited by surface condition. The penetration for aluminum is < 50 µm but for some other material such as titanium the penetration is not exceed < 5 µm [28].

3.2 Uncertainty of hole drilling method

In hole drilling method there are many source for the uncertainty firstly; in the test system the source of uncertainty are alignment of the hole, gauge circle dimensions and stress and temperature resulting from drilling, secondly; in test procedure the calculation of stresses is a factor of uncertainty.[29]. Experiments or equipment can be redesigned to reduce the effects of these parameters. However it is not limited to these parameters, some of the other factors were identified and it may important, such as drill speed and feed, operator skill, drill wear, excitation voltage, quality of gauge installation, and data reduction methods [30, 31]. It is very difficult to consider all parameters in measurement when determining the uncertainties in hole drilling methods. Often few uncertainties parameters will apply to measurement in the field and laboratory [29].

Usually, the results of the measurements of residual stresses using most of the measuring techniques are given as a single unique value for a particular set of conditions. Differences in result between laboratories using same methods indicate uncertainties of the method used [30, 31], and can be used for comparative purposes only but the results are not reasonable when requires the related uncertainty that could be expected at a particular location in a material.

4. Conclusion

Most of the engineering components contain compressive or tensile residual stresses. Residual stresses affect the component life which is prolong by compressive residual stresses and decreased by tensile residual stresses. Accordingly, it is important to measure the magnitude of the residual stresses.

In engineering materials, there are many schemes for the measuring of residual stresses. In selection of a measurement schemes from the available schemes, it is important to think about some factors such as materials types; metal, polymer, or composite, type of stresses; macro or micro stresses, cost; expensive or inexpensive, sample size; small or big and measurement technique; destructive or non-destructive. However, each method has its on advantages and disadvantages, Table 1 summarized some residual stress measurements technique's advantages and disadvantages.

Table 1: Advantages and Disadvantages of Some Residual Stress Measurement Techniques

Technique	*Advantages*	*Disadvantages*
X ray diffraction	Versatile, widely available, wide range of materials, macro and micro residual stress	Basic measurements, lab based systems, small components
Hole drilling	Quick, simple, widely available, wide range of materials, deep hole drilling for thick section components	Interpretation of data, destructive, limited strain sensitivity and resolution
Synchrotron	Improved penetration and resolution of X-ray, depth profiling, fast, macro and micro	Specialist facility, only lab based

	residual stress	
Neutron diffraction	Excellent penetration and resolution, 3D maps, macro and micro residual stress	Specialist facility, only lab based
Magnetic	Very fast, wide variety of magnetic techniques, portable.	Only ferromagnetic materials, 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
Contour	High resolution maps of stress normal to the surface, wide range of materials	Interpretation of data, destructive

5. Future Scope

In order to optimize residual stress measurement techniques, laser shearography technique is proposed. Laser shearography technique is a technique that uses image processing to obtain the data. By using this technique, the time taken to obtain the results will be faster; tested sample is not affected by external factors where these factors might change the actual strain and stress. Compared to some residual stress measurement techniques like X-ray diffraction technique and neutron diffraction technique which obtain the results from lab-based systems, laser shearography technique can be carried out by using portable system; one of benefit is on-site inspection and testing.

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