Enliven Archive
Intensifying Thoughts

Research Article www.enlivenarchive.org Enliven: International Journal of Advances in Civil Engineering

The State-of-Art Methods for Residual Stress Evaluation

SB Singh[1], Aparajita Singh[2]*

[1] *Professor of Civil Engineering Department, BITS Pilani-333031, Rajasthan, India.*
[2] *Process Engineer, INTEL USA Corporation Ltd, Hillsboro, OR, USA.*

[*]Corresponding Author: S.B. Singh, Professor of Civil Engineering Department, BITS Pilani-333031, Rajasthan, India, E-mail: sbsinghbits@gmail.com/ sbsingh@pilani.bits-pilani.ac.in

Received Date: 23rd October 2019
Accepted Date: 05th December 2019
Published Date: 12th December 2019

Citation: SB Singh, Aparajita Singh. The State-of-Art Methods for Residual Stress Evaluation. Enliven: Int J Adv Civil Eng.2019; 2(3):9-8.

Abstract

This chapter deals with description of the state–of-art methods for residual stress determination. As any stress quantity, residual stress has multi-component tensor nature. Also, unlike the live stresses, residual stresses cannot be determined by tracking their evolution from an initial state. Also, residual stresses are scale-dependent and hence if the gauge volume of the measurement is changed, the perceived stress state also gets changed. In this context, residual stresses are often classified into Type I (Macro-Scale Stress), Type II (Micro-Scale Stress) and Type III (Nano-scale stress). Various papers based on challenges of measuring residual stresses and measurement techniques were reviewed and described herewith. Description of various conventional as well as latest techniques for residual stress determination such as those based on (a) destructive and non-destructive methods and (b) qualitative and quantitative approach. Namely the methods such as X-ray diffraction method, Hole-drilling method, Neutron diffraction method, photo-stress coating method, curvature method, Magnetic and Eddy current techniques, and Eigen strain approach are described in the following sections.

Keywords: Curvature Method; Crack Compliance method; Destructive and Non-destructive Techniques; Eddy Current Techniques; Residual Stress; Hole-Drilling Method; Eigen-strain; Magnetic Method; and XRD technique.

Introduction

Residual stress is defined as the stress that exists in the body of a member not being subjected to external forces. The residual stresses develop due to forming and/ or processing operation as well as by environmental conditions. These stresses can arise due to (i) mechanical effects; which generate residual stresses by producing plastic deformation as result of processes during production or treatment, however, the residual stresses can be introduced mechanically into a component to develop a particular stress profile. (ii) thermal effects; in this case residual stresses can be generated due to heating or cooling processes which in combination with material limitation develop internal stresses caused due to severe thermal gradients., and (iii) chemical effects; in this case, reaction such as precipitation can generate residual stress in a component due to volume change. Moreover, the chemical surface treatment, coating and nitriding can also generate residual stresses.

The residual stresses affects the performance and durability of many different natural and engineered systems [1] such as plants, sea shells, bone and dental tissues, electronic parts and electro-chemical systems (batteries and fuel cells), and most-importantly structural components and assemblies which are used in infrastructure systems, transport sectors, and civil engineering construction sector. Furthermore, residual stresses affect the stability, response, and progressive failure characteristics of structural components during its service conditions. Thus these residual stresses affect the evolution of systems from initial intended structural and mechanical state that may result in loss of bond between parts of the system resulting in fracture or voiding or excessive deformation or distortion. Currently, it has become clearer that degradation processes that limit the lifetime and performance of systems begin at the finest atomic and molecular scales, progress through the nano-and micro-scale, and finally lead to failure manifesting themselves at millimeter to meter to kilometer ranges.Resdual stresses can be categorized in three types as per their extension levels [2-6], namely (a) 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, (b) Type-II: these stresses extend over a distance of one grain or a part of it, and (c) Type –III: these stresses appear in very small portion of material and vary within several atomic distances in the grain limits.

Thus measurement of residual stress is important in predicting service life, analyzing distortions, and determining the cause of failure. It may be noted that the residual stresses can be desirable or undesirable depending upon its nature, for example,

residual stress in a surface of a component can be either tensile in nature or compressive in nature. The near surface tensile residual stresses tend to accelerate initiation and growth phases of the fatigue process while compressive residual stresses close to the surface may prolong fatigue life [7]. Mostly, surface tensile residual stresses are undesirable [2]. Welding, machining and grindings are examples of operations that generate surface tensile stresses. Tensile residual stresses may increase the rate of damage by fatigue, creep or environmental degradation and lead to the capacity reduction caused due to failure by brittle fracture or by other modes of damage such as shape change or fine cracks on the surface. It has also been stated by authors [7-8] that residual stresses can raise or lower the mean stress experienced over a fatigue cycle. Welding is one of the most significant cause of the tensile residual stress. The magnitude of residual tensile stresses developed by welding could be of the order of material yield strength.

Tensile residual stress in the welded component or elements can be reduced to the minimum level possible by appropriate selection of welding process, welding materials, fabrication sequence, and structural geometry. In addition, low stress no-distortion welding techniques can also reduce the tensile residual stress. In addition to the above, shot peening and low plasticity burnishing could be also employed to introduce compressive residual stresses to minimize the undesirable tensile residual stresses. Thus introducing near surface compressive residual stresses through plastic deformation and or overloading condition could improve the performance of components such as increased fatigue life.

In this paper, a state-of-art review of the techniques and/ or methods or evaluation or measurements of residual stress is presented for their application and challenges associated with each technique. A range of techniques is available but each has a number of disadvantages and it is unlikely that a single technique will be feasible for variety of situations in practice. Thus it is essential to provide review of various techniques with their appropriate application in conjunction with their disadvantages/ limitations and challenges. For easy understanding of the measurement techniques for residual stress, the measurement techniques have been classified into two categories: (1) Destructive Techniques and (2) Non-destructive techniques. Description of various destructive and non-destructive techniques is given below in subsequent sections.

Destructive Techniques for Residual Stress Measurement

The destructive techniques of residual stress evaluation are those that destroy the sample for relief of stresses for example curvature method, hole drilling method, and compliance method. Description of each of the destructive techniques are given below:

Curvature Method

The curvature method is often used to determine the residual stresses within coatings and layers. The deposition of layers may cause substrate to curve. The changes in curvature during deposition can be used to determine the corresponding variation in the stress as a function of deposit thickness. Curvature can be measured with the using profilometry or strain gages based on their direct contact with sample or specimen. While other methods such as Video, laser scanning grids, double crystal diffraction topology can be used to measure change ins curvature without direct contact. It may be noted that curvature measurements are usually made on narrow strips having width to length ratio ≤0.2 to avoid multi-axial curvature and mechanical stability [2]. As per Stoney [9] formula, the residual stresses in a coating or thin films can be calculated using Eq. 1.

$$\sigma = \frac{E_s}{6(1-v_s)} \frac{h_s^2}{h_f} \left(\frac{1}{R} - \frac{1}{R_0} \right) \quad \text{------ (1)}$$

where

Es is the Young's modulus; v_s is the Poisson's ratio and h_s is the thickness of the substrate; h_f is the thickness of the film; R and R_o are the radii of curvature of the substrate after and before deposition. The Stoney formula as given above is based on the following hypotheses [9]:

- The thicknesses of the substrate and the coating are smaller than the lateral dimensions;
- Deformations and rotations are infinitesimal;
- The substrate and the coatings are homogenous, isotropic, and linear elastic;
- The radius of curvature is equal in all directions (i.e., spherical deformation);
- The stress and radius of curvature are constant on the whole surface of the plate.

It may be noted that the Stoney formula is frequently used, even if the above hypotheses are not completely respected. Also, there are several methods available in literature for determination of curvature. For example, Masters and Salamon[10] and Harper and Whu[11] used punctual curvatures measured in the centre and at a quarter of sample while Ngo et al. [12] showed that the film stress depends on the curvature of the entire susbstrate. The authors [12] extended the Stoney formula for non-uniform misfit strain distribution. In an another approach, Fillon [13] monitored the evolution of stress using a multi-beam optical stress sensor technique. In this method, hypothesis of uniformity of curvature was assumed and substrate curvature was measured in two orthogonal directions. For each direction, they took six measurements and the average value was considered. Ardigo et al. [9] in their study measured Silicon substrate curvature before and after TiN film coating taking into account the whole surface and determined the residual stress using the Stoney formula. It is demonstrated that the deformation is influenced by the shape of the substrate. The authors [9] stated that the choice of radius (i.e., maximum, minimum or mean value) is critical for the determination of the stress. It is also put in evidence that when the shape of sample approaches a strip, the deformation after coating tends to become more spherical which is in agreement with data available in literature.

Crack Compliance Methods

The crack compliance method is most suitable for simple geometry where stresses vary in one direction only. In this method, a component is instrumented with a number of strain gauges. A slot is then made into the component by some convenient techniques such as electric-discharge machining. Changes in

the strain gauge readings are recorded as the slot is extended. From these readings, it is original residual stress components along the line of the slot is predicted.

Nowell et al. [14] have described the application of the dislocation density method to the calculation of compliance functions required for the analysis of experimental data regarding changes in surface strain as a slot is cut. The kernel functions for specimens of finite thickness such as beam and plates are provided. It has been demonstrated by means of numerical solution that the accuracy of results could be improved by the use of multiple gauge locations. However, the major disadvantages of the crack compliance method are the possibility of multiple solutions and the lack of appropriate mathematical framework for the treatment of errors. Some sample results have been presented for the case of plastically bent beam. It is shown that the method is capable of accurate predictions of the residual stresses close to the top surface from which cut is made. However, the predictions are less satisfactory when the point is away from the surface of cut. But the quality of results could be improved by using additional gauges on the bottom face. It has been concluded that the compliance method is appropriate where the thickness of slot is negligible compared with its depth. Thus the slot can be modelled as a crack of zero thickness. The crack solution is found to be accurate for most practical geometries [15].

The crack compliance technique is destructive , however, it offers the advantages of low cost and potentially good accuracy for a number of common situations.

Hole Drilling Method

The hole drilling method is mostly used method for residual stress evaluation. This method measures released strains due to boring a small hole and the released strain is measured by strain gauge rosettes glued around the hole in the area of interest where residual stresses are to be measured. The rosette typically consists of three strain gauges arranged at 0 degrees, 90 degrees, and 135 degrees around a centre point where hole is drilled. Figure 1 shows a magnified photograph [16] of hole-drilling strain gauge. These rosettes are commercially available in several sizes and geometries ranging from 1.6 mm to 6.3 mm hole diameter. In this method, it is assumed that material is isotropic, linear elastic, and the variations of stress within the boundaries of the hole are small.

For cracks originating just below the surface down to a depth of 2mm or for distortion issues in thin parts, this method is found to be most common. Walker [16] in his article has stated thathole-drilling method is accurate and sensitive for measuring residual stresses from the surface to a depth of about 2 mm or more. In this method, maximum depth of measurement is limited by the diameter of the hole drilled by the ultra-high speed mill. The maximum depth sensitivity of the three strain gages built into the strain rosette is 0.7 times the diameter of hole [16].

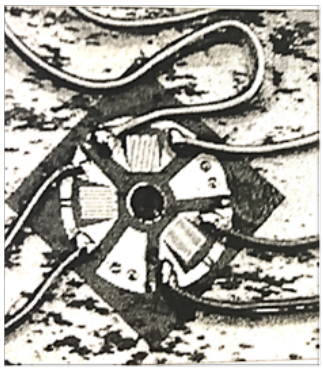
In the above discussion, it has been assumed that the hole is drilled centrically towards strain gauge rosette. However, the hole is eccentric to the strain gauge rosette. Svaricek and Vlk [17] have described the Vangi's method [18] for residual stress determination with an eccentric hole. This method has used correction for elimination of the deviation of strains due to eccentricity. But these corrections are valid for a thin plate with through hole. In the paper [17], necessary calibration coefficients have been determined and relaxed strains are simulated for eccentricity 0.2 mm for uniaxial, the equi-biaxial and the shear state stress and for the strain gauge rosette RY 61 S. 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).

The advantages of the hole-drilling method is that the method can be used on large components and in-situ because the hole-drilling equipment is portable. Also, the actual test is quick and inexpensive and can be done wide range of materials with curved or flat surfaces [19]. The limitation of the hole drilling method [2] is that the relieved strain decay rapidly with depth into the metal so the detection is sensitive to near surface stresses and is variable with depth. Also, this method is susceptible to errors due to position of holes, depth (measured and controlled to 1 micro meter), diameter and concentricity (must be within ±0.025 mm). The drilling process can induce stresses and to minimize this high speed drilling is used. The process is destructive and errors are difficult to interpret. Also, the errors may be introduced by the surface roughness and flatness.

Non-Destructive Methods

The non-destructive techniques of residual stress evaluation are those that do not destroy the sample for evaluation of residual stresses, for example Eigenstrain approach, Magnetic method, Eddy current method, Utrasonic methods, X-Ray Diffraction Method, and Neutron diffraction method. Description of each of the destructive techniques are given below:

Figure 1. Photograph of a hole-drilling strain gauge rosette in place after measurement [16].



Eigenstrain Approach

Recently, the Eigenstrain approach to predict the residual stresses has got considerable interest. This is due to the fact that it is possible to reconstruct the residual stress field of a component starting with a set of residual stress measurements on a baseline sample with reasonable computational time [20]. The eigenstrain indicates any permanent or non-elastic strain generated inside a component after a non-elastic process. The term eigenstrain has also been referred as inelastic strain [21], inherent strain[22], and equivalent transformation strain [23]. The other strains such as creep strain, phase transformation strain, thermal strain, etc. can be incorporated into the term eigenstrain. As these non-elastic strain componentes cannot be separated , this property becomes an advantage when eigenstrain is applied into an Finite element model. This eigenstrain approach is mathematically found to be complicated and hence found to be feasible only for simple geometry samples with limited engineering applications. The results obtained from application of eigenstrain prediction have been presented for applications such as friction stir welding [24], shot peening [25], and Laser Shock Peening (LSP) [26]. These results are partially or completely based on the model proposed by Korsunsky. The model proposed by Korusnky is called Eigenstrain Reconstruction Method (ERM). Details of this method can be found in the reference [27]. With Eigenstrain Reconstruction Method, the whole residual stress field within a body can be determined with availability of a bunch of measurements. It is divided into three steps, i.e., the measurement of the residual stress field in a certain area of the sample; the calculation of the eigenstrain values, and the application of the eigenstrain values to the same sample to know its entire residual stress field. It may be noted that although the method has shown its versatility in different fields, the calculation of the eigenstrain is strictly dependent on the researcher's experience in making the correct choice of the polynomial fit used to predict the eigenstraindistributioner. It has also been demonstrated that in spite of indirect derivation of the eigenstrain from experimental residual stress data, physically it is more accurate than that extracted from an finite element model that may not accurately reproduce either the residual stress or plastic strain field that led to it.

X-ray Diffraction (XRD) Method

In this method of predicting residual stress, the strain in the crystal lattice is measured and the residual stress is determined using the elastic constant with assumption of linear elastic distortion of a crystal lattice plane. In this case, X-rays impinge over an area of sample wherein many grains and crystals contribute the measurement. The exact number is dependent on the grain size and geometry of the beam. Although the strain measurement is considered to be near surface, the x-rays penetrate some distance into the material where penetration depth depends on the anode, material, and angle of incidence. Thus the measured strain [28] is essentially the average over a few microns depth under the surface of the specimen.

The X-ray diffraction method is non-destructive and is applicable to crystalline materials with relatively small or fine grain size. The material may be metallic or ceramic provided that a diffraction peak of suitable intensity and free of interference from neighbouring peaks can be produced. In a National Measurement Good Practice Guide [28], XRD measurement rec-

Figure 2. Coordinate system used for calculating surface strains and stresses [28].

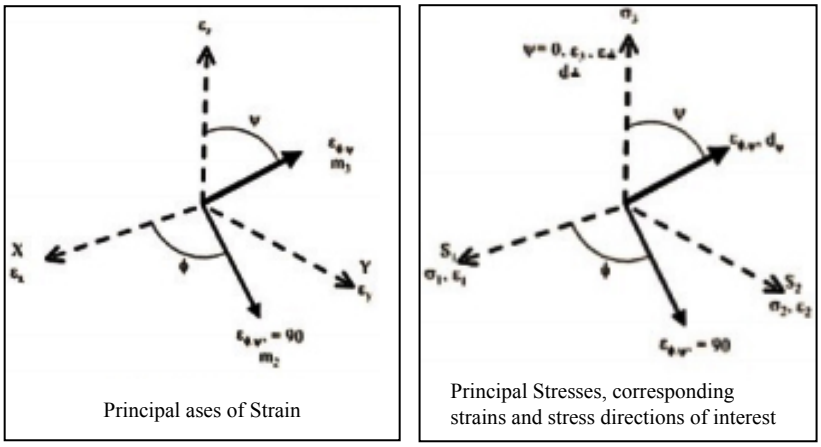
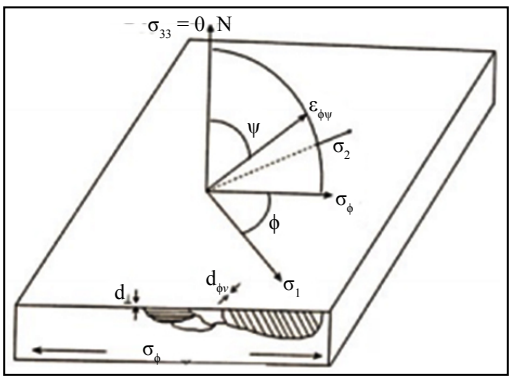


Figure 3. Schematic showing diffraction planes parallel to the surface and at angle [28].



ommendations are meant for stress analysis using the peak shift only. However, if a full triaxial analysis of stress is performed using a stress-free reference, absolute peak location has to be determined. The reference [28] assumes that the measurement are made with assumption that the stress normal to the surface is zero, plane stress condition.

To perform a strain measurement, the specimen is placed in the X-ray diffractometer and it is exposed to an X-ray beam that interacts with the crystal lattice to cause diffraction patterns. The diffraction peaks are located by scanning through an arc of the radius. It is known that the thereis clear relationship between the diffraction pattern observed when X-rays are diffracted through crystal lattices and the distance between atomic planes i.e, interplanar spacing within the material. By changing the inter-planar spacing, different diffraction patterns areobtained. Furthermore, changing even the wavelength of the X-ray beam results in a different diffraction pattern. The inter-planar spacing of a material that is free of strain will produce a characteristic diffraction pattern for that material. When a material is strained, elongations and contractions are produced within the crystal lattice, which results in change of the inter-planar spacing of the {hkl} lattice planes. This induced change in inter-planar spacing, d, will cause a shift in the diffraction pattern. Thus the strain deduced in the material can be determined by evaluating the change in the inter-planar spacing which is evaluated by the precise measurement of the shift of the X-ray diffraction pattern. A mathematical relationship between the inter-planar spacing and strain is established below.

As the measurement is made within the surface, stress normal to the surface,σ_3=0, but the strain ε_z (normal to the surface) is not equal to zero. The strain, ε_z can be measured experimentally by measuring the peak position, 2θ and solving Eq. 2 for a value of d_n.

n λ= 2d sinθ ----- (2)

Normal strain,

$$\varepsilon_z = \frac{d_n - d_o}{d_o} \quad \text{----- (3)}$$

Where d_o is unstrained inter-planar spacing.It may be noted that the strain within the surface of the material can be measured by comparing the unstressed lattice inter-planar spacing with the strained inter-planar spacing. However, there is need to precisely measure the unstrained inter-planar spacing.By altering the tilt of the specimen within the diffractometer, measurements of planes at angle ψ (See Fig.3) can be made and thus the strains along that direction can be determined using Eq. 4.

$$\varepsilon_\psi = \frac{d_{\psi\phi} - d_o}{d_o} \quad \text{------ (4)}$$

Fig. 3 shows planes parallel to the surface of material and planes at angle ϕψ to the surface. This illustrates how planes that are at an angle to the surface are measured by tilting the specimen so that planes are brought into position where they will satisfy the Bragg's law given by Eq.2.

If we assume that at the surface of the material, where the X-ray measurement can be considered to have been made and that ,σ_z = 0 then,

$$\varepsilon_z = -\nu\left(\varepsilon_x + \varepsilon_y\right) = -\frac{\nu}{E}\left(\sigma_x + \sigma_{y\sigma}\right) \quad \text{------ (5)}$$

Thus combining Eqs. 3 and 5, we have

$$\frac{d_n - d_o}{d_o} = -\frac{\nu}{E}\left(\sigma_x + \sigma_y\right) \quad \text{----- (6)}$$

Note that Eq. 6 applies to a general case, where only the sum of the principal stresses can be obtained and the precise value of do is still required.

To measure a single stress acting in some direction in the surface, σ_ϕ. Elasticity theory for an isotropic solid shows that the strain along an inclined line (m3 in Fig.2) is given by:

$$\varepsilon_{\psi\phi} = \frac{1+\nu}{E}\left(\sigma_1 \cos^2\phi + \sigma_2 \sin^2\phi\right)\sin^2\psi - \frac{\nu}{E}\left(\sigma_1 + \sigma_2\right) \quad \text{----- (7)}$$

If we consider the strains in terms of the inter-planar spacing, and use the strains to evaluate the stresses, then it can be shown that

$$\sigma_\phi = \frac{E}{(1+\nu)\sin^2\psi}\left(\frac{d_\psi - d_o}{d_n}\right) \quad \text{------ (8)}$$

Eq. 8 allows us to calculate the stress in any chosen direction from the inter-planar spacings determined from two measurements, made in a plane normal to the surface and that containing the direction of the stress to be measured. The most commonly used method for stress determination is the $\sin^2_\psi$ method. In this method, a number of XRD measurements are made at different tilt angles, ψ. The inter-planar spacing or 2θ peak position is measured and plotted as a curve similar to that shown in Fig. 4.

Fig. 4 can be used to calculate stress by determining the gradient of the line and with basic knowledge of the elastic properties of the material. This assumes a zero stress at d=dn, where d is the intercept on the y-axis when $\text{Sin}^2\psi = 0$. Thus the stress is given by Eq. 9.

$$\sigma_\varnothing = \left(\frac{E}{1+\nu}\right)m \quad \text{------ (9)}$$

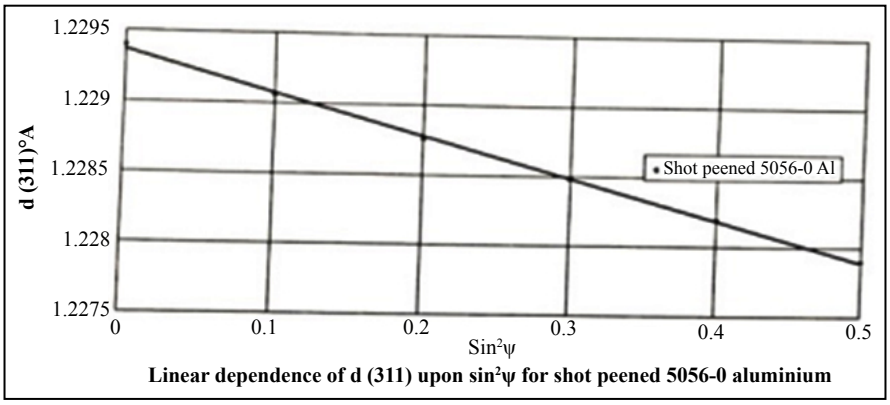
Where m is the gradient of the d vs $\sin^2\phi$ curve.

Magnetic Method

This method is magnetic in nature and therefore limited to ferromagnetic materials. Because of the phenomenon of magnetostriction, magnetic properties such as permeability depend sensitivey on stress. The working principle of this method for a steel bar can be described as below [29].

Suppose that the test bar is inserted in a solenoid and subjected to an axial magnetic field and that the bar also has a secondary coil wound on it. If the frequency of applied a-c magnetic field is very low(a few cycles/sec), then the field H is essentially uniform throughout the cross-section of the bar. The voltage

Figure 4. Example of inter-planar spacing, d vs $\sin^2_\phi$ plot.



Linear dependence of d (311) upon $\sin^2\psi$ for shot peened 5056-0 aluminium

induced in the secondary coil is then a function of the magnetic properties averaged over the entire section of the bar. However, if the frequency is high, the eddy currents which are generated will shield the inside of the bar from the applied field and only the outer portion will be magnetized. The secondary-coil output will then reflect the magnetic properties of only the outer portion. If the bar is residually stressed, then both the stress and magnetic properties vary from axis to the surface, and this variation will cause the secondary coil output to vary in a different way with frequency than if the bar is stress free.

There are two magnetic methods: (i) magnetostriction and (ii) Barkhausen noise. The magentorestriction method as discussed above is based on the measurement of permeability and magnetic induction [29] while the Barkhausen noise method is based on the analysis of magnetic domain wall motion [30-31]. If magnetostrictive materials are stressed, preferred domain orientations are altered. This makes domains most nearly oriented to a tensile stress to grow (i.e., positive mgnetorestriction) or shrink (i.e., negative magnetorestriction). 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 component surface by a sensor coil. If there is no rotation, then the principal axes of magnetic field and stress are parallel. When the assembly is rotated, both the principal stress directions and the size of principal stress difference can be measured.Magnetoaccoustic 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.

Barkhausen emission on the other hand is recorded as a change in the electro motive force (emf) proportional to the rate of change in magnetic moment detected by probe coil as domain walls move. It is attenuated at high frequencies by eddy current shielding and so provides only a near surface probe (< 250 micrometer). It may be noted that the magnetic methods have the advantage of providing cheap and portable method for non-destructive residual stress measurement. Recently, Sorsa et al. [32] based on Barkhausen noise measurement predicted the residual stress and hardness of a case-hardened steel samples. A data based approach for building a prediction model has been proposed by the authors. This approach consists of feature generating, feature selection and model identification and validation steps.

Ultrasonic Methods

This method is based on changes in the ultrasonic speed when the material is subjected to a stress. This change in ultrasonic speed is a measure of the stress averaged along the wave path. The acoustoelastic coefficients which are necessary for the analysis are usually calculated using calibration tests. Different types of the waves 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. The basic equation for the stress calculation is as follows:

$$V = V_o + K\sigma \text{ ------ (10)}$$

Where V_o is the velocity of a wave in an unstressed medium, σ is the stress, and K is a material constant known as acoustoelastic constant.

Recently, Kudryavstev et al. [33] have presented details of ultrasonic technique and device for residual stress measurement. Authors have highlighted the importance of ultrasonic method as non-destructive technique for residual stress measurement. An Ultrasonic Computerized Complex (UCC) non-destructive technique for measurement of residual and applied stress has been described. It has been concluded that the developed ultrasonic method and associated portable instrument along with supporting software can be used for non-destructive residual stress analysis in laboratory samples and real structure elements for a wide range of materials. Furthermore, it has been highlighted that the expert system allows analyzing effects of welding residual stresses and their redistribution under the effect of cyclic loading and various improvement treatments on the fatigue life of welded elements.

References

[1]. Korsunsky AM. A Teaching Essay on Residual Stresses and Eigenstrains. Butterworth-Heinemann; 2017 Jun 8.

[2]. Zaroog OS, Ken2b CY, Manap1c AN. Current and Challenge of Residual Stress Measurement Techniques. evaluation. 2014;6(8):10.

[3]. Withers PJ, Bhadeshia HK. Residual stress. Part 1–measurement techniques. Materials science and Technology. 2001 Apr 1;17(4):355-65.

[4]. Borland DW. Residual stress measurement--methods, limitations and significance. Quality Control and Assurance in Advanced Surface Engineering. Institute of Materials, 1 Carlton House Terrace, London, SW 1 Y 5 DB, UK, 1997.. 1997:113-25.

[5]. Noyan IC. Defining residual stresses in thin film structures. Advances in X-ray Analysis. 1991;35(A):461-73.

[6]. Niku-Lari A. Advances in surface treatments. Elmsford, NY (USA); Pergamon Books Inc.; 1987 Jan 1.
[7]. Webster GA. Role of residual stress in engineering applications. InMaterials Science Forum 2000 (Vol. 347, pp. 1-11). Trans Tech Publications.
[8]. Landgraf RW, Chernenkoff RA. Residual stress effects on fatigue of surface processed steels. InAnalytical and experimental methods for residual stress effects in fatigue 1988 Jan. ASTM International.
[9]. Ardigo MR, Ahmed M, Besnard A. Stoney formula: Investigation of curvature measurements by optical profilometer. InAdvanced Materials Research 2014 (Vol. 996, pp. 361-366). Trans Tech Publications.
[10]. Masters CB, Salamon NJ. Geometrically nonlinear stress-deflection relations for thin film/substrate systems with a finite element comparison.
[11]. Harper BD, Chih-Ping W. A geometrically nonlinear model for predicting the intrinsic film stress by the bending-plate method. International journal of solids and structures. 1990 Jan 1;26(5-6):511-25.
[12]. Ngo D, Feng X, Huang Y, Rosakis AJ, Brown MA. Thin film/substrate systems featuring arbitrary film thickness and misfit strain distributions. Part I: Analysis for obtaining film stress from non-local curvature information. International journal of solids and structures. 2007 Mar 15;44(6):1745-54.
[13]. Fillon A, Abadias G, Michel A, Jaouen C. Stress and microstructure evolution during growth of magnetron-sputtered low-mobility metal films: Influence of the nucleation conditions. Thin Solid Films. 2010 Dec 30;519(5):1655-61.
[14]. Nowell D, Tochilin S, Hills DA. Measurement of residual stresses in beams and plates using the crack compliance technique. The Journal of Strain Analysis for Engineering Design. 2000 May 1;35(4):277-85.
[15]. Nowell D. Strain changes caused by finite width slots, with particular reference to residual stress measurement. The Journal of Strain Analysis for Engineering Design. 1999 May 1;34(4):285-94.
[16]. Withers PJ, Bhadeshia HK. Residual stress. Part 1–measurement techniques. Materials science and Technology. 2001 Apr 1;17(4):355-65.
[17]. Svaricek K, Vlk M. Residual stress evaluation by the hole-drilling method with eccentric hole. Engineering Mechanics. 2007 Jun 15;14(3):191-7.
[18]. Vangi D. Residual stress evaluation by the hole-drilling method with off-center hole: an extension of the integral method.
[19]. Lord J. Hole drilling techniques. InBCA Structural Materials Workshop 2000.
[20]. Coratella S, Sticchi M, Toparli MB, Fitzpatrick ME, Kashaev N. Application of the eigenstrain approach to predict the residual stress distribution in laser shock peened AA7050-T7451 samples. Surface and Coatings Technology. 2015 Jul 15;273:39-49.
[21]. Reissner T, Appl J. Eigenspannugen und Euigenpannungensquellen. Math. Mech. 1931;1:1-8.
[22]. Murakawa H, Deng D, Rashed S, Sato S. Prediction of distortion produced on welded structures during assembly using inherent deformation and interface element. Transactions of JWRI. 2009;38(2):63-9.
[23]. Eshelby JD. The determination of the elastic field of an ellipsoidal inclusion, and related problems. Proceedings of the Royal Society of London. Series A. Mathematical and Physical Sciences. 1957 Aug 20;241(1226):376-96.
[24]. Luckhoo HT, Jun TS, Korsunsky AM. Inverse eigenstrain analysis of residual stresses in friction stir welds. Procedia Engineering. 2009 Jul 1;1(1):213-6.
[25]. Korsunsky AM. The modelling of residual stresses due to surface peening using eigenstrain distributions. The Journal of Strain Analysis for Engineering Design. 2005 Nov 1;40(8):817-24.
[26]. Achintha MN, Nowell D, Shapiro K, Withers PJ. Eigenstrain modelling of residual stress generated by arrays of laser shock peening shots and determination of the complete stress field using limited strain measurements. Surface and Coatings Technology. 2013 Feb 15;216:68-77.
[27]. Jun TS, Korsunsky AM. Evaluation of residual stresses and strains using the eigenstrain reconstruction method. International Journal of Solids and Structures. 2010 Jun 15;47(13):1678-86.
[28]. Fitzpatrick ME, Fry AT, Holdway P, Kandil FA, Shackleton J, Suominen L. NPL measurement good practice guide no. 52. Determination of Residual Stresses by X-ray Diffraction. NPL Teddington, UK. 2005.
[29]. Abuku S, Cullity BD. A magnetic method for the determination of residual stress. Experimental Mechanics. 1971 May 1;11(5):217-23.
[30]. Abuku S, Cullity BD. A magnetic method for the determination of residual stress. Experimental Mechanics. 1971 May 1;11(5):217-23.
[31]. Gauthier J, Krause TW, Atherton DL. Measurement of residual stress in steel using the magnetic Barkhausen noise technique. Ndt & E International. 1998 Feb 1;31(1):23-31.
[32]. Sorsa A, Leiviska K, Santa-aho S, Lepisto T. Quantitative prediction of residual stress and hardness in case-hardened steel based on the Barkhausen noise measurement. Ndt & E International. 2012 Mar 1;46:100-6.
[33]. Kudryavtsev Y, Kleiman J, Gushcha O, Smilenko V, Brodovy V. Ultrasonic technique and device for residual stress measurement. InX International Congress and Exposition on Experimental and Applied Mechanics. Costa Mesa, California USA 2004 Jun 7:1-7.