Residual stresses and X-rays

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Residual stresses can have significant effects on the fatigue lives of components and are particularly important in surface treatments such as shot peening. X-ray stress analysis provides a nondestructive method for measuring the residual stress in a shallow surface layer of material approximately 10 μm thick. Layer removal techniques such as electropolishing allow the evaluation of the residual stress profile through the material. Reliable and accurate dedicated X-ray stress analysers are available that enable measurements in less than 0.5 h analysis time. The X-ray technique is described and some examples are presented of its applications. Additionally, difficulties that have been experienced with this technique are discussed.

*Keywords*: residual stresses, X-ray stress analysis, surface layers, fatigue life

Residual stresses can have a significant effect on the service performance of engineering components and a note on their formation is given in Appendix 1. The most popular methods for measuring both applied and residual stresses employ metal foil strain gauges, stress relaxation being achieved by the centre-hole and ring-core techniques. The centre-hole method is based on the relaxation of stress which occurs at the edge of a small hole drilled in the material. A strain gauge is used to measure the strain release around the hole. Conversely, the ring-core method relies on the stress relaxation of an island of material after trepanning around it with a cutter. Again, a strain gauge is employed to allow computation of the residual stresses from the released strain. However, there are nondestructive techniques based on other physical principles – magnetic, ultrasonic, neutron and X-ray diffraction – that can be used to measure residual stress. The principles of the X-ray stress analysis technique are presented as Appendix 2.

Although the X-ray technique is based on physical principles familiar to crystallographers, the information it provides is mainly used by engineers and metallurgists for product development. The variation of interplanar spacing with orientation of a particular set of crystallographic planes is related to residual stress and forms the fundamental of X-ray stress analysis. Lester and Aborn in 1925 showed that applied stress changed the interplanar spacing. Since then, the X-ray technique has been developed by many workers into a reliable, accurate, fast but expensive (high capital cost) stress analysis method.

This paper describes some typical X-ray techniques including camera and diffractometer methods used to measure residual stress. Examples of the application of the technique to the measurement of residual stress in components will be detailed as well as some problems encountered with it.

**Camera techniques**

Usually, flat pinhole cameras containing an X-ray film are used in the back-reflection method to expose the film to diffracted radiation from the specimen material. The X-ray beam passes through the centre of the camera where a collimator restricts its divergence.

The specimen-to-film distance can be determined using a standard powder. Initially, the author used standard Ag powder with a known crystal structure (2θ = 156° for (420) planes, Co radiation) but later changed to using a long collimator and distance gauge for accurate setting of the camera position.

High diffraction angles (with 2θ as near to 180° as possible) are measured to improve precision and for steel, using Co radiation. (310) crystal planes give an angle 2θ = 161°. Many laboratories use Cr radiation which gives a reflection from steel at 2θ = 156° for the (211) planes.

Although most cameras are circular, as are the diffraction rings, the author started his X-ray stress analysis using a rectangular camera. One advantage with circular cameras is that they allow multi-exposure of the film. Two diametrically opposite sectors of the film are exposed to the radiation and are subsequently rotated, thus enabling the same film to be used for, say, four exposures. This saves material costs and processing time and eliminates shrinkage errors between films.

If the diffraction rings are well defined, their diameters are measured using a modified travelling microscope.

However, the diameters of broad, diffuse rings, caused by small grain size and non-uniform strain, cannot be measured accurately by this method but necessitate the use of a microdensitometer. Generally, a two-exposure method was used and the residual stress σr determined from
Measurements of the ring diameters were made from an exposure normal to the specimen surface and another at an angle of 45°. From a knowledge of the specimen-to-film distance and radiation wavelength, the interplanar spacings \( d_0 \) and \( d_{45} \) were calculated using Bragg's law. Subsequently, the residual stress was calculated using the elastic constants for the material, Young's modulus \( E \) and Poisson's ratio \( \mu \).

Although the camera technique is no longer used by the author to measure residual stress, it is used to obtain a rapid qualitative assessment of the texture and grain size of a material. The camera technique is very time consuming and one analysis could take up to one day to complete. In addition, its accuracy is limited for broad diffraction rings, although diffractometer techniques improve both speed and accuracy.

**Diffractometer techniques**

Geiger, proportional and scintillation counters used with scalers and ratemeters have enabled automation of the X-ray technique. A microprocessor can be used to control all operations of the diffractometer and the counter data can be processed to provide the residual stress value and other information.

The Strainflex X-ray stress analyser manufactured by the Rigaku Corporation, Japan, uses a scintillation counter and a scaler to provide intensity (or count) and angular position \( (2\theta) \) data for microprocessor analysis. The counter is rotated by a stepping motor at a fixed radius from the measurement position. Counting is undertaken for a set time at angular positions from \( 2\theta = 170° \) to 140°. The peak position, \( (2\theta) \) corresponding to the maximum intensity is determined from the count data for the angle of incidence \( \psi_0 \) of the primary X-ray beam. Typically, the time taken for an analysis including four angles of incidence \( (\psi_0 = 0°, 15°, 30° \text{ and } 45°) \) on ferritic steel is 0.5 h.

Counters have improved the accuracy and shortened the time for an analysis. The most recent development is the position-sensitive proportional counter (PSPC) incorporated in some manufacturers' systems (eg TEC, USA). The detector is in the form of a wire which produces a signal at each end when X-rays are incident on it. The rise time of the signals enables position location along the wire. Because the detector spans the whole \( 2\theta \) angular range of a diffractometer profile, it eliminates the scanning operation and significantly improves analysis time.

The Fastress X-ray system supplied by the American Analytical Corporation employs two X-ray sources to irradiate the same area of a component. Dual detectors simultaneously determine the position of the two peaks for 0° and 45° incidence. The angular difference between the peak positions is related to the residual stress and output on a chart recorder. Analyses can be undertaken in approximately 20 s and the equipment is used for quality control of components, eg peened gears.

Manufacturers have considerably reduced the size of X-ray hardware to improve the accessibility of diffractometers and their portability. X-ray tubes supplied for the Strainflex system are much smaller than conventional tubes, eg 0.46 kg compared with 2 kg. One American analyser is capable of making measurements along a 254 mm bore in stainless steel pipe. Portable systems dedicated to X-ray stress analysis are available from several manufacturers (eg Rigaku, TEC, Denver Instruments).

**Applications**

The technique has many applications for determining the surface residual stresses in components. Using the Strainflex system, analyses can be made on isotropic material having a suitable grain size from an area \( 2 \times 2 \) mm\(^2\), enabling determination of the stress gradient across the surface to an area \( 5 \times 20 \) mm\(^2\). Also, by taking analyses in three directions separated by 60° intervals, it is possible to compute the principal stresses at that position. Through-thickness residual stress profiles can be obtained by machining layers of material from the surface and taking X-ray stress analyses at each depth. The machining stresses induced in the surface layers of material can be removed by electropolishing prior to X-ray analysis. However, when measuring the depth profiles of residual stress, suitable corrections have to be made to the measured stresses to account of the effect of removing a layer of material on the stress distribution beneath it.

Although the technique has been used on many components, most of the work at Swinden Laboratories has been concerned with coil and Taperlite springs. Taperlite springs are leaf springs parabolically tapered, which results in a uniform bending stress along their length, and they are stress peened to give very high residual compressive stresses in the surface. Using the methods described, it has been possible to demonstrate the effectiveness of different prestressing operations applied to leaf springs. Presetting (reverse bending the spring to some multiple of the yield stress) can produce favourable tensile residual stresses of approximately 200 N mm\(^{-2}\) in the lower face of the spring. Free peening of the upper face will induce compressive residual stresses of approximately \(-400 \) N mm\(^{-2}\) and stress peening (reverse bending plus peening) will double the compressive stresses to approximately \(-800 \) N mm\(^{-2}\). This residual compression enables the Taperlite spring to operate at much higher service stresses, because the actual stress in the spring is the algebraic sum of the tensile service stress and compressive residual stress.

Because the X-ray beam only penetrates approximately 10 µm into the surface of a component, the technique is ideal for the evaluation of surface treatments. Comparisons can be made between different types of machining (grinding, milling, turning) and other surface treatments (surface hardening, shot peening). The variation of residual stress with depth is shown in Figure 1 for polished, turned and shot-peened components.

**Calibration, coarse grains and texture**

No residual stress measurement technique is without its problems and the X-ray stress analysis technique is no exception. The bulk elastic constants are often used in the calculation of the residual stress, but it is incorrect to use these values unless the stresses are being used for comparison purposes. Only particular crystallographic planes contribute to the diffraction profile and these have to be orientated correctly to diffract the X-ray beam. Because only a very thin surface layer is examined which
is effectively unconstrained on one side, the elastic constants for the crystal planes at the surface of the component may differ somewhat from the bulk values.

These problems can be overcome by calibrating the technique for the material being analysed. A suitable beam specimen can be made from the material and a strain gauge attached to it. The specimen is placed in a four-point bending rig and bending stresses (measured using the strain gauge) applied to it. X-ray measurements are made alongside the strain gauge, allowing calibration of the X-ray measured stress.

Course-grained and textured material can also create problems by offsetting the diffraction peak from its true position. A large grain or higher concentration of small grains can contribute most to a diffraction peak, shifting it from its true position (ie if all the grains were the same size and in the same concentration). In order to overcome these problems, large grain size (> 30 μm), the number of grains contributing to diffraction must be increased in some way. Using the camera technique, this can be done by oscillating the film in the horizontal plane. It is possible to oscillate the component or incident beam in the vertical plane when using counting systems. With large components the latter is preferable. Therefore more grains are favourably orientated and able to diffract the X-ray beam.

A technique called the fixed Ψ can be used to improve analyses on textured material. Both the X-ray tube and counter can be rotated to search for the diffraction conditions for a particular concentration of crystallographic planes. Because the plane concentration is being kept constant, the correct peak position should be located for them.

Concluding remarks

Many developments have taken place in X-ray diffraction hardware, some of which have subsequently been applied to residual stress analysis. Systems are available that are dedicated to stress analysis and offer fast and reliable analyses as well as compactness and light weight so that the systems can be transported for site applications.

Advances have taken place, predominantly in Japan, West Germany, the USA and France, at a much faster pace than in the UK. Often X-ray diffractometers intended for crystallographic applications are used for stress analysis. However, the author is aware of three dedicated stress analysers imported over the last few years.

A User Group was established in 1983 under the auspices of the British Society for Strain Measurement to discuss future development and applications of the technique. Consequently, there is more awareness and confidence in the technique, with a demand for residual stress data on high-tech components.

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Appendix 1. The formation of residual stresses

Often residual stresses are termed 'locked in' or 'fast' stresses because they exist in a material when no external forces are applied to it. A number of manufacturing processes create a stress gradient through a component consisting of elastic and plastic stresses and these give rise to residual stresses, eg rolling, heat treatment, forming, welding, machining.

To illustrate the formation of residual stresses, the presetting process applied to a leaf spring to produce the correct camber height and beneficial residual stresses can be used (Figure 2). The spring shown is being reverse bent to residual stress analysis. Systems are available that are dedicated to stress analysis and offer fast and reliable analyses as well as compactness and light weight so that the systems can be transported for site applications.

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so that the bending stresses at the surfaces exceed the yield stress of the material. When the bending moment is removed, the material that has been plastically deformed wishes to remain extended in length on the upper surface and reduced in length on the lower surface. However, the material, behaving in an elastic manner, tries to return to its original length. Considering the upper surface, the elastic layers of material place the plastic layers in compression and the plastic layers are responsible for tensile stresses in the subsurface elastic layers. A similar explanation holds for the lower surface, although when a material is yielded in compression the residual stresses produced in it are tensile, while in the regions elastically deformed the residual stresses are compressive.

Although the nature of the residual stress distribution in a leaf spring can be predicted from the bending operation given to it, some distributions, after, say, machining, require measurement to determine the nature as well as the magnitude of the residual stress. Analyses are undertaken on leaf springs to optimize the residual stress pattern produced by the presetting operation in order to maximize spring performance.

Appendix 2. The X-ray stress analysis technique

Let us consider a solid cylinder of polycrystalline material. The crystal planes within the material are randomly distributed, with some parallel to the cylinder axis and others perpendicular to it. If a force is applied along the axis, some planes are forced closer together while others are forced wider apart, depending upon their orientation to the axis. The difference between the interplanar spacings $d$ for planes at different orientations can be related to the stress $\sigma$ in the material by

$$\sigma = \left( \frac{E}{1 + \mu} \right) \left( \frac{1}{\sin^2 \psi} \right)$$

where $E$ is Young's modulus and $\mu$ is Poisson's ratio for the material. The interplanar spacing for planes in stress-free material is $d_0$, while $\psi$ relates to the orientation of the planes and is shown in Figure 3.

When an X-ray beam is incident on a material, it is reflected by planes with a specific orientation to the beam and produces a high-intensity diffraction peak. The interplanar spacing of the planes and angular position are related to each other by Bragg’s law

$$\lambda = 2d \sin \theta$$

where $\lambda$ is the wavelength of the radiation and $2\theta$ is the angular position of the diffraction peak (shown in Figure 3).

Differentiating Bragg’s equation and substituting into Equation (1) gives

$$\sigma = -\left( \frac{E}{2(1 + \mu)} \right) \cot \theta_0 \left( \frac{\pi}{180} \right) \left( \frac{\Delta 2\theta}{\Delta \sin^2 \psi} \right)$$

where $\theta_0$ is the diffraction angle for stress-free material.

This equation can also be used to calculate residual stress. A counter can be used to measure $2\theta$ directly for a particular incident angle of the X-ray beam. By measuring the value of $2\theta$ at, say, four incident angles ($\psi_0 = 0^\circ, 15^\circ, 30^\circ$ and $45^\circ$), a linear relationship is found for an isotropic material of $2\theta$ against $\sin^2 \psi$ (obtained by calculation). The slope $\Delta 2\theta/\Delta \sin^2 \psi$ can be substituted into Equation (2) together with other appropriate constants to enable calculation of the residual stress. This technique is referred to as the fixed $\psi_0$, $\sin^2 \psi$ technique.

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