

Residual Stress Measurement using X-Ray Diffraction Techniques, Guidelines and Normative Standards

Mohammed Belassel
Proto Manufacturing Inc.

ABSTRACT

Several residual stress (RS) measurement standards that employ x-ray diffraction (XRD) techniques are available for users in Europe, North America, Japan and other countries. Such standards are similar in principle however the detailed requirements for each standard are different. RS measurements performed on critical components require a good knowledge of XRD techniques and current best practices so that they can be correctly applied to the challenging geometries and exotic materials that often compose critical components of interest. This paper will compare the key requirements found in the various RS measurement guidelines and standards currently available to users while emphasizing and justifying current best practices as they apply to the measurement of RS on mechanical components used in the automotive and the aerospace industry.

CITATION: Belassel, M., "Residual Stress Measurement using X-Ray Diffraction Techniques, Guidelines and Normative Standards," *SAE Int. J. Mater. Manf.* 5(2):2012, doi:10.4271/2012-01-0186.

INTRODUCTION

Residual stress measurements in materials using XRD techniques have been widely applied in industry, at universities, and in research and development laboratories to help develop new products and to optimize new and existing processes. It is also utilized to help understand deformation mechanisms in materials subjected to fabrication processes and to mechanical testing such as fatigue. To analyze the data correctly, high quality measurements are required; as such, equipment operators must be aware of all the "ins and outs" of the technique. Operators must be conversant with the application itself as well as the advantages and limitations of the measurement techniques applied. Operators must also be aware that each technique possesses characteristics that may differ from others. The XRD technique is usually limited to the surface of the material and the measurement of stress below the surface normally requires some material removal. Moreover, the material microstructure and the processes applied to it can generally be interpreted by analysis of the XRD peak shape; this is one of the advantages the XRD technique offers. In this paper, emphasis will be placed on the XRD technique and its detailed requirements and capabilities as documented in the many existent guidelines and standards, national or international such as: EN 15303 [4], ASTM E915-10 [3] and others. The objective is therefore to help the user acquire the best measurement practices and ultimately be successful in his/her endeavors. The focus will be on the

major aspects of XRD stress measurement and details that will help users obtain high quality results will be provided.

STRESS MEASUREMENT USING X-RAY DIFFRACTION TECHNIQUE

The x-ray diffraction technique uses the distance between crystallographic planes, i.e. d-spacing, as a strain gage. This method can only be applied to crystalline, polycrystalline and semi-crystalline materials [1]. When the material is in tension, the d-spacing increases and when the material is in compression, the d-spacing decreases. The presence of residual stresses in the material produces a shift in the x-ray diffraction peak angular position that is directly measured by the detector [2].

For a known x-ray wavelength λ and n equal to unity, the diffraction angle 2θ is measured experimentally and the d-spacing is then calculated using Bragg's law:

$$n\lambda = 2d \sin \theta \quad (1)$$

where λ is the wavelength of the radiation.

Once the d-spacing is measured for unstressed (d_0) and stressed (d) conditions, the strain is calculated using the following relationship:

$$\varepsilon = (d - d_0)/d_0 \quad (2)$$

For the $\sin^2\psi$ method where a number of d-spacings are measured, stresses are calculated from an equation derived from Hooke's law for isotropic, homogeneous, fine grain materials:

$$\begin{aligned} \varepsilon_{\phi\psi} = & \frac{1}{2}S_2(\sigma_\phi - \sigma_{33})\sin^2\psi + \frac{1}{2}S_2\sigma_{33} - S_1(\sigma_{11} + \sigma_{22} + \sigma_{33}) \\ & + \frac{1}{2}S_2\tau_\phi\sin 2\psi \end{aligned} \quad (3)$$

where:

$\frac{1}{2}S_2$ and S_1 are the x-ray elastic parameters of the material.

σ_ϕ is the stress in the direction of the measurements.

ψ is the angle subtended by the bisector of the incident and diffracted beam and the surface normal.

$\varepsilon_{\phi\psi}$ is the strain at a given ψ tilt.

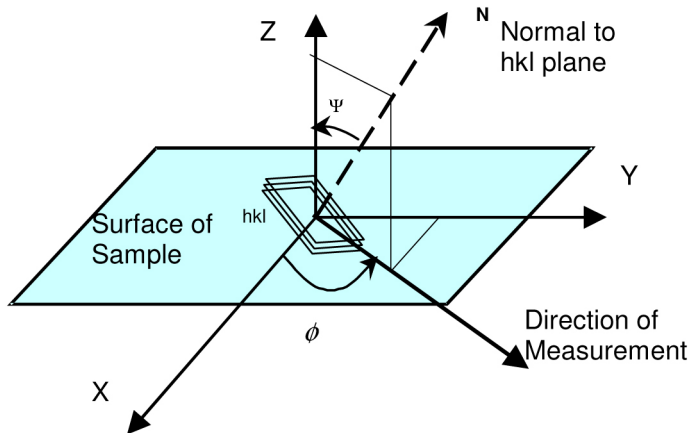


Figure 1. Definition of the axis and the direction of measurement

SYSTEM QUALIFICATION AND SYSTEM ALIGNMENT

SYSTEM QUALIFICATION

Inherent tolerance in the XRD goniometer production and assembly is inevitable, therefore fictitious shear and normal stresses are always present. This is the reason why goniometers are equipped with an adjustment system to minimize their displacement while rotating about the center of concentricity. The acceptable resultant stress values due to mechanical misalignment are stated in most of the current guidelines and standards. As per ASTM E915-10 [3] (when measuring steel), the stresses measured on a stress free reference material should not exceed 14 MPa and should normally be no greater than 7 MPa. A similar value is

proposed in the European EN15305 [4] standard under a different definition using the X-Ray elastic constant in such a way that 20 displacements are computed. The expressions of interest in EN15305 are as follows:

$$|\sigma| \leq \frac{1}{10000} \cdot \frac{1}{\frac{1}{2}S_2^{hkl}} \text{ and } |\Delta\sigma| \leq \frac{1}{10000} \cdot \frac{1}{\frac{1}{2}S_2^{hkl}} \quad (4)$$

$$|\tau| \leq \frac{1}{20000} \cdot \frac{1}{\frac{1}{2}S_2^{hkl}} \text{ and } |\Delta\tau| \leq \frac{1}{20000} \cdot \frac{1}{\frac{1}{2}S_2^{hkl}} \quad (5)$$

SHEAR STRESSES

Shear stresses are usually present in materials and can be observed for many reasons. They can be caused by the following:

1. Goniometer misalignment: beam and sample displacement.
2. Normal offset: normal at the location of the measurement does not coincide with the normal to the sample.
3. Non uniform strains: heterogeneous materials (steel with carbides)
4. Fabrication processes.

SYSTEM ALIGNMENT

XRD diffraction systems require alignment of the x-ray beam and the mechanical movement. If it is not performing as per the requirement, a fictitious stress may be measured on a stress free material. This is called a systematic error that is added to all measured stresses and can also introduce artifacts that will alter the measurements. According to equation (3) that is widely employed in XRD stress measurement, 2 types of stresses can be measured for a single direction: normal stress σ_ϕ and shear stress τ_ϕ . This can be seen as an ellipse with a slope on the d-spacing vs. $\sin^2\psi$ plot. If a shear stress is not present, the ellipse closes and becomes a straight line. Furthermore, if no normal stress is present, the slope of the ellipse or line is zero. The opening and slope of the ellipse or line is also dependent upon the goniometer geometry selected i.e. if the goniometer is working in Omega or Psi mode or in another non-standard mode such as Modified Psi or grazing incidence.

EFFECT OF CURVATURE

When curved specimens are considered, two main parameters can affect the stress results:

1. The surface normal offset
2. The size of the diffraction spot