On Using the One-Exposure Method for Stress Measurements by X-Rays in Technology and Scientific Research

by

H. E. A. Saleh
Physics Dept., Faculty of Education,
Ein Shams University, Cairo — Egypt.
and
I. Kraus
Faculty of Nuclear Science and Physical Engineering, Prague.

ABSTRACT

The paper discusses the connection between macroscopic internal stresses and the technological character of technical materials. The basic theoretical relations which are used with X-Ray tensiometry of macroscopic internal stresses, and the principle of the method of one exposure, are introduced. The ability of their utilization in technology is illustrated through the examples of measuring macroscopic internal stresses of runner blades and through the determination of the yield point of steel.

Introduction

Internal stresses are important factors, not only for the optimization of technological production, but also for the reliability of their products. The later employment of mechanical and x-ray methods for measuring internal stresses in metals introduced the ability to determine experimentally the state of residual stresses and its nature in longitudinal directions and cross-sections of the material surface under investigation. It is now time for metallurgical and industrial technology to take more care about the measuring of internal stresses and about the analysis of their effects on the behaviour of every individual operation in manufacturing processes and on the mechanical properties of the products.

Most of the information about internal stresses which are introduced in connection with technological parameters of materials, dating from the beginning of the Thirties, is now out of date. This is due to the complication of the internal structure of modern technical materials, and to the essential different forms of their strains.

To determine exactly the relation between internal stresses and, for example, the state of deformation through cutting or reshaping, or between internal stresses and static and dynamic stresses, hardness or corrosion, we need more systematic experimental work. This needs co-operation between experts in technical manufacturing and physicists.

The aim of this paper is to show the possibility of solving those questions about internal stresses in technical material using x-ray diffraction methods in concrete examples.

The Main Reason For Internal Stresses Formation In Metals

We can define internal stresses as those stresses existing in a closed system, S, with no effect from external forces and moments. The forces and moments which arise under the effect of internal stresses are at mechanical equilibrium in systems S. This means that the resultant force calculated with respect to any free plane — inside S — must equal zero, and also for the resultant momentum with respect to any axis of rotation passing through S.

The formation of internal stresses depends mainly on deformation, temperature and structure transformation. Under the effect of these factors we can recognize three main types of internal stresses — deformation, thermal and transformation. (Internal stresses may also arise through electropolishing, e.g., chrome plating, and may have technical significance.)

Deformation and thermal internal stresses are formed through inhomogeneous plastic deformation, which is developed in the first case by external forces only, and in the second case by quick change of temperature only, without any change of structure (transformation).

Internal stresses due to deformation are formed, for example, through plastic bending, rolling, or through inelastic tensile stresses, specially in those cases where crystals near the surface deform in a different way from those inside the block. The character of deformation internal stresses is that its sign opposes the sign and direction of the pre-given stress.

Thermal internal stresses are formed, for example, in hardened steel samples under the effect of great thermal gradients perpendicular to the surface. The external parts of the sample are cooled more quickly than its internal parts, so tensile stresses are created in the inner part while on the surface compressive stresses are created. Later, when the inner part is cooled it compresses again on the outer parts of the sample, and finally a typical compressive state of stresses is formed on the surface for thermal internal stresses.

Through rolling or polishing a residual compressive surface stress was obtained. Residual stresses were also formed by cutting the metal. Compressive stress existed to a depth of some sixteenth of a millimetre and increased with the depth of cut and with the worn out edge of the knife. After some new accurate measurements it was found that on the surface there were tensile residual stresses (0.01 mm.), which then became compressive.

Grinding is a method of treatment with high thermal effects. From the point of view of some authors grinding forms tensile stresses, while others measure compressive stresses which are changed after a depth of 10^{-2} mm. to tensile stress. Change of sign can be clarified on the basis of thermal and mechanical effects.

Compressive stresses arise in mechanical hardworking of the surface layer through cold treatment or through grinding the surface, and may reach a value of 10^2 MPa. The amount of this stress decreases almost in the inner direction of the surface, and so after a distance of 0.1-0.2 mm., is practically negligible.

Transformation internal stresses are formed through inhomogeneity through the subsequent transformation of structure which is connected with the volume effects, as for example, in the case of martensitic transformation.

Surface transformation exerts pressure on the nucleus. Untransformed austenite nucleus deforms in a plastic way so that the least tension results in it. When the transformation of the nucleus increases, the surface regions will be subject to plastic deformation. For this reason the result is the rising of tensile stresses on the surface.

Independent of these original effects, the internal stresses can be differentiated within the range of the stress field to their different natures.

Macroscopic internal stresses — internal stresses of the first kind — are practically homogeneous for x-ray measurements of the inner part of the sample. Equilibrium exists only when we consider the whole sample. Inequilibrium leads always to a macroscopic change of dimensions. All mechanical and combined mechanical/x-ray methods for measuring internal stresses are dependent on this fact.

Microscopic internal stresses — internal stresses of the second kind — change due to the direction, size and orientation of every single crystal in the domain. With respect to internal forces and moments, those stresses are in equilibrium in such domains, comparable with the x-ray measured regions. For this reason the resultant magnitude of stresses are zero in these macroscopic zones (domains).

Submicroscopic internal stresses — internal stresses of the third kind — are adjusted into very small lattice domains of radius dimensions about some interatomic distances. They have their origin in point and line lattice defects. Neither microscopic nor submicroscopic internal stresses can induce macroscopic changes in dimension.

Different types and kinds of internal stresses do not occur as isolated cases. Generally we obtained more than one type and kind in the same assembly. For example, internal stresses which arise through hardening are superpositioned over all other types and kinds.

The Principle of Using X-Ray Methods

Homogeneous lattice deformation is formed as a result of elastic stresses in macroscopic domains of polycrystalline materials. This tends to change Bragg's angle by an amount, $\delta\theta$, through x-ray diffraction, which means a change in the position of diffraction lines. Using the diffractometer, $\delta\theta$, can be directly determined. Through the method of back-reflection, where the diffracted rays are registered on a flat film, it is first required to determine the magnitude of the line shift δr.

Following the differentiated Bragg equation, we note that for a given δ d/d, the change $\delta\theta$ increases by increasing the angle θ

$$\frac{\delta d}{d} = - \text{Catan}\ \theta \,.\, \delta\theta \tag{1}$$

For this reason, the region of back-reflected rays is always used to measure the lattice deformation. From the arrangement of Debye-Scherrer's method for back-reflection (Figure 1) we obtain —

$$\delta r = - \frac{2D}{\text{Cos}^2\ 2\ \theta}\ \delta\theta \tag{2}$$

Using Equations (1) and (2) we have —

$$\frac{\delta d}{d} = \frac{\text{Cotan}\ \theta\ \text{Cos}^2\ 2\ \theta}{2D}\ \delta r \tag{3}$$

To be able to determine lattice deformation due to internal stresses using x-ray, we must return to the frame of the theory of linear elasticity.

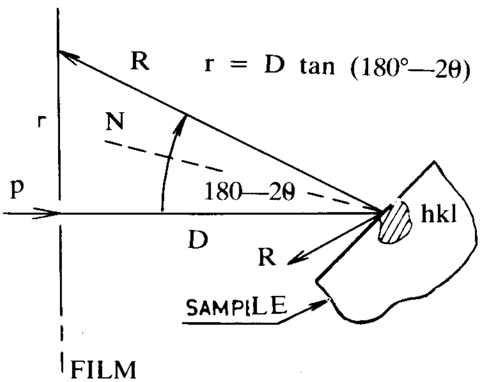

Figure 1

Schematic arrangement of Debye-Scherrer method for back-reflection. P, R are primary and reflected x-ray beams, N is the normal to the system of reflecting planes, D is the distance between the sample and the film, and r is the radius of the basis of the diffraction cone.

In the case of three dimensional state of stresses with principal

stress σ_3 perpendicular to the surface and principal stresses σ_1 and σ_2 laying on the surface, we find for the deformation —

$$\left(\frac{\delta d}{d}\right)_{\varphi,\psi} = \varepsilon_{\varphi,\psi}$$

in the direction defined by the angles φ, ψ (Fig. 2), the equation —

$$\varepsilon_{\varphi,\psi} = \tfrac{1}{2} S_2 (\sigma_1 \mathrm{Cos}^2 \varphi + \sigma_2 \mathrm{Sin}^2 \varphi - \sigma_3) \mathrm{Sin}^2 \psi + S_1 (\sigma_1 + \sigma_2 + \sigma_3) + \tfrac{1}{2} S_2 \sigma_3 \quad (4)$$

where —

$$\frac{1}{2} S_2 = \frac{\nu + 1}{E}, \; S_1 = - \frac{\nu}{E} \quad (5)$$

E and ν are Young's modulus of elasticity and Poisson's ratio respectively.

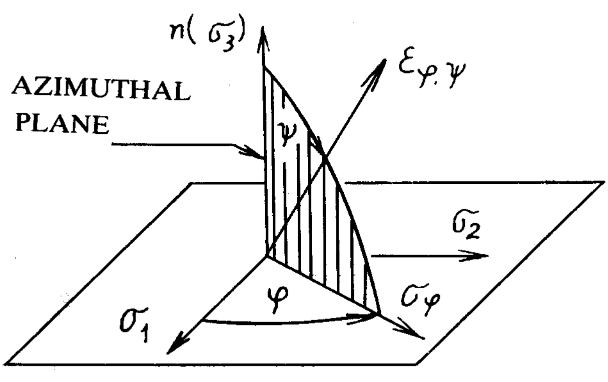

Figure 2

The character of the direction of measuring the deformation $\varepsilon_{\varphi\psi}$; σ_1, σ_2, σ_3, are the principal stresses, n is the normal to the sample surface and σ_φ is the surface stress component having the azimuthal direction φ

With respect to the undefined depth of penetration of x-rays, we can neglect the effect of stress σ_3 — perpendicular to the surface — on the lattice deformation. For this reason, we can use in all practical cases the two dimensional state of stresses. For the deformation $\varepsilon_{\varphi\psi}$ we obtain —

$$\varepsilon_{\varphi\psi} = \frac{1}{2} S_2 (\sigma_1 \mathrm{Cos}^2 \varphi + \sigma_2 \mathrm{Sin}^2 \varphi) \mathrm{Sin}^2 \psi + S_1 (\sigma_1 + \sigma_2) \qquad (6)$$

and —

$$\varepsilon_{\varphi,\psi} = \frac{1}{2} S_2 \sigma_\varphi \mathrm{Sin}^2 \psi + S_1 (\sigma_1 + \sigma_2) \qquad (7)$$

respectively, where —

$$\sigma_\varphi = \sigma_1 \mathrm{Cos}^2 \varphi + \sigma_2 \mathrm{Sin}^2 \varphi \qquad (8)$$

is the surface component of the stress applied in the direction defined by the angle φ, ψ with respect to σ_1.

In any free azimuthal plane (e.g., for φ = const.,) we obtain a linear dependence of the deformation $\varepsilon_{\varphi,\psi}$ on $\sin^2 \psi$. Practically, equation (7) is applied in case of x-ray tensiometry to find the stress component σ_φ and to calculate the main stresses $\sigma_1 + \sigma_2$ (Fig. 3).

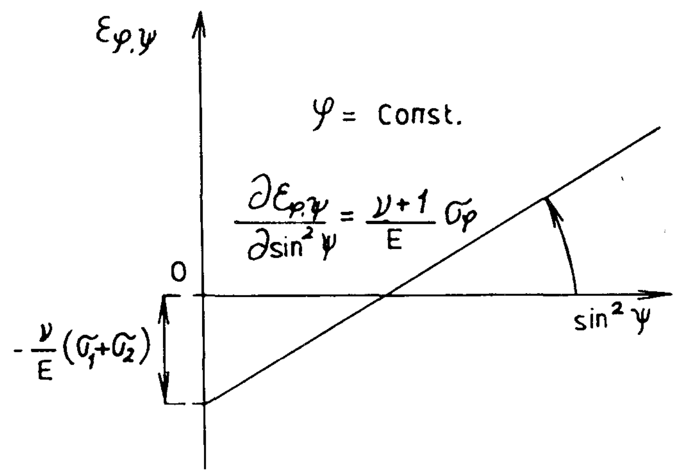

Figure 3

The dependence of $\varepsilon_{\varphi = \mathrm{const.}, \psi = 0}$ on $\sin^2 \psi$.

The deformation $\varepsilon_{\varphi = const, \psi}$ is determined in an elected plane for a known angle ψ. Then σ_{φ} can be obtained from the line slope K of the line $\varepsilon_{\varphi = const, \psi}$ ($\sin^2 \psi$) using the relation —

$$K = \frac{1}{2} S_2 \sigma_{\varphi} = \frac{\nu + 1}{E} \sigma_{\varphi} \tag{9}$$

Calculation of principal stresses $\sigma_1 + \sigma_2$ is given from the magnitude of $\varepsilon_{\varphi = const, \psi = 0}$ as —

$$\sigma_1 + \sigma_2 = \frac{\varepsilon_{\varphi' = const, \psi = 0}}{S_1} = -\frac{E}{\nu} \varepsilon_{\varphi = const, \psi = 0} \tag{10}$$

We propose here, that the narrow monochromatic x-ray beam P makes an angle ψ_O with the surface of the stressed material in the azimuthal plane containing both the primary beam and the normal to the surface n (Fig. 4).

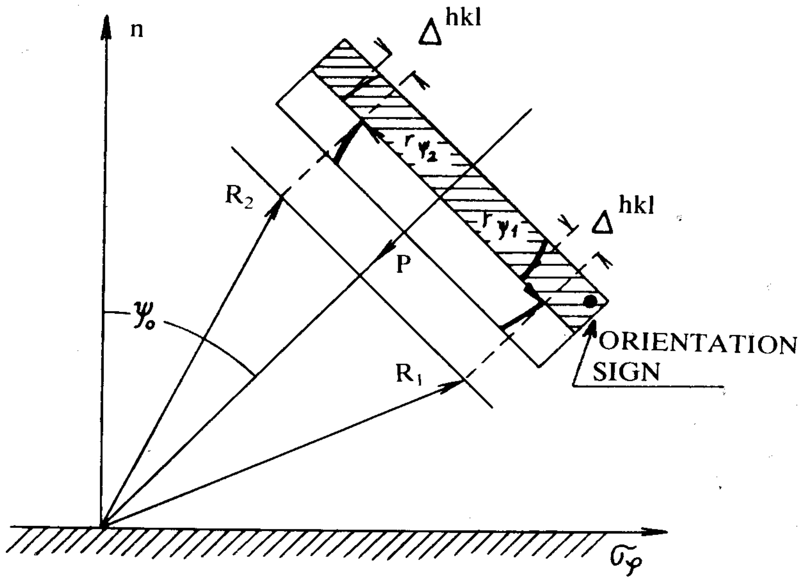

Figure 4

Diffraction figure obtained by two exposures of the selected region of the material surface subjected to tensile stresses for $\psi_O \neq O$.

To detect the diffracted radiation, a film in a rectangular cassett was used, then the cassett was mounted so that its longitudinal axis lay in the plane containing the normal to the surface and the direction where the stress component $\sigma\varphi$ is measured. Before the exposure took place we covered the upper half of the film with a protective mask which absorbs the diffracted radiation. Only the lower part of the diffraction ring will be registered. When the exposure was finished the cassett and film were rotated by 180° about an axis coincident with the primary beam, and we again covered the upper part of the film with the protective mask. Nothing was changed in the experimental arrangement, i.e., the radiated region of the surface and the angle ψ_O were the same. The exposure took place again. After development of the film we obtained a discontinuous distribution of diffraction lines on both the left and right sides of the film. We identified the radial shift of these discontinuous lines by Δ^{hkl} (the shift in the direction of the longitudinal axis of the film.) With reference to Fig. 4, we can write —

$$\Delta^{hkl} = r_1 - r_2$$

If the effect in the azimuthal direction (φ) is a tensile stress,

then we have $\Delta^{hkl} > 0$, while in case of compressive stress we have $\Delta^{hkl} < 0$.

To determine the value of macroscopic stress in the direction φ, $\psi = \pi/2$ we have for an incident angle of the primary beam on the material surface $\psi_O = 45°$, the relation —

$$\sigma\varphi = \frac{\varphi + 1}{E} \frac{\text{Catan } \theta \text{ Cos}^2 2\theta}{2D} \frac{\Delta^{nkl}}{\text{Sin}^2 2\eta} \quad , \eta = 90° - \theta \qquad (11).$$

If the distributed diffraction lines on both halves of the film are continuous, then $\Delta^{hkl} = 0$ and also $\sigma\varphi = 0$.

We can also determine the stress sign (tensile or compressive) at once with reference to the relative blackening intensity of the inner and external arc lines. If the intense line (more blackened) has the minor radius, then we have a tensile stress, and vice versa.

Examples of Experimental Results

To illustrate the utilization of x-ray diffraction in determining the residual macroscopic stresses, we started with the results of measurements which had been done on the surface of runner blades manufactured from special chrome (nickel steel). For the tensiometric investigation of these products the method of back-reflection was used. This method depends on one x-ray diffraction pattern measured with the use of the Debye-Sherrer arrangement. This method is known as the one-exposure method without reference material (its principle was introduced at the end of the section entitled "The Principle of Using X-Ray Methods.")

X-ray measurement of macroscopic internal stresses was applied to the blades B_1 and B_2 which differed in their thermal treatment. Blade B_1 was heated to 1150° C., annealed for a period of 4 hours at 680° C., quenched in oil at 140° C. and finally yielded for 4 hours at a temperature of 380° C. For blade B_2 no thermal treatment was done.

The selected face of the blade to be measured was ground by soft emery paper (to eliminate rough impurities) and then was electrically etched to release the stresses which were mechanically formed in the surface layer.

Calculation of internal stresses using Equation (11) and Δ^{hkl} for discontinuous diffraction lines (211) was done for the reflected $K\alpha$ radiation of chromium anode on Fe — α .

The collection of the results of these measurements shows that :

(a) for both blades only tensile stresses were found, independent of the selected place or direction of measurement, while its magnitude depends on the place of the surface area under study as well as on the direction of measurement;

(b) internal stresses on blade B_1 were varied within the limits of 350-480 MPa; and

(c) for blade B_2 which was not thermally treated, internal stresses had generally a larger magnitude, that is, between 500-800 MPa.

Error of measurements did not exceed 10% in any case.

The results of this concrete example, can serve as an illustration of using x-ray tensiometry for the control of thermal treatment of steel, both for introducing a definite technological method to the relation between residual macroscopic stresses, and to thermal treatment.

A similar method as in the above example was an x-ray determination of the yield point in samples of steel.

The stress σy which was developed by pure bending at the point of maximum deflection of the plate sample, was calculated from the magnitude of Δ^{310}, after the substitution of Poisson's ratio $\nu = 0.28$ and Young's modulus E = 2058×10^{2} MPa.

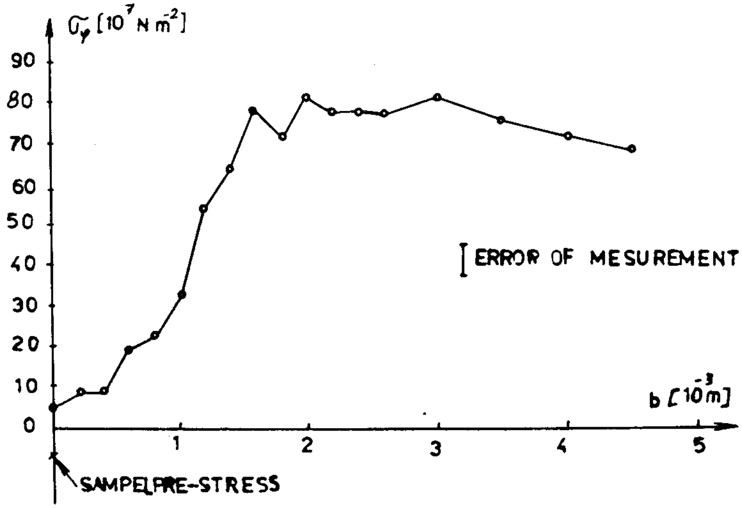

Figure 5

The characteristic behaviour of the relation between the tensile stresses, developed by pure bending of the surface layer of steel plates under study, and the bending (b).

As is seen from Fig. 5, when there is no surface bending, e.g., b = o, we still obtain some value for the compressive stresses ($\sigma\varphi < 0$) This compressive stress was due to the mechanical treatment of the material, and for this reason the material was chemically etched before carrying out any measurement.

The dependence of $\sigma\varphi$ on (b) shows that an evident decrease of tensile stress on the sample surface is found at bending b > 3 mm. For this material, the mechanical value of the yield point was 735 PMa, as determined from the tensile test.

Besides these two examples, where x-ray tensiometric methods were used to solve technological engineering problems, the authors had applied x-ray measurements of internal stresses in basic research of plastic deformation of metal materials. [1, 2, 3].

CONCLUSION

The essential part of general knowledge which we have today about the character of technical materials, is based on historical development of our experience with material treatment.

In connection with strain, the concept of strength, brittleness and so on arises. The result of such development is actually that technological parameters are not exactly defined from the physical point of view. This is precisely the main origin of the difficulties with which we are faced if we want to understand and introduce the relation between internal stresses and technological variables in a quantitative form.

The method of x-ray diffraction is the only method which permits non-destructive measurements of internal stresses. It represents a particular situation between the tensiometric methods which are known at present. Up until now this method has been mostly applied only under laboratory conditions, because of the time spent in photometric plotting of diffraction patterns and the difficulties connected with the evaluation of stresses through the interpretation of lattice deformation. Today the research is directed, for example, towards the study of the elastic and plastic character of metal, or the determination of internal stresses which arise during the manufacturing of important parts of some machines.

In industry, the main use for x-ray tensiometry is found to be for controlling the production of antifriction bearings and to determine the internal stresses developed in welding boilers or other expensive constructions. Another main reason utilizing the method of x-ray tensiometry in basic research of the properties of metal materials and in machinery practice, is the automation of measuring methods and the expanding of physical knowledge for engineers, metallurgists and engineering industries.

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حـول استخدام طريقة التعريض الأحادى لقيـاس الأجهاد بواسطة الأشعة السينية في التكنولوجيا والبحث العلمـي

ح . أ . صـــالح ، أ . كرواس

كلية العلوم ـ جامعة قطر و كلية الطبيعة النووية والهندسة ـ

الجامعة التكنيكية ببراغ .

ملخـــــــص

يتعرض هذا البحث لمناقشة العلاقة بين الاجهاد الماكروسكوبى الداخلي والخواص التكنولوجية للمواد المعدنية المستخدمة في الصناعة . حيث يقدم الأساس للعلاقات النظرية المستخدمة مع القياس التنسومترى للاجهاد الماكروسكوبي الداخلي بواسطة الأشعة السينية ، وكذلك الأساس الذي بنيت عليه طريقة التعريض الأحادى . ويوضح البحث إمكانيـة استخدام هذه الطرق في التكنولوجيا خلال أمثلة من قياسات الأجهاد الماكروسكوبي الداخلي على الشفرات المروحية وكذلك خلال تعيين حد الأذعان للصلب .