# ASPECTS OF RESIDUAL STRESS DETERMINATION BY X-RAY DIFFRACTION

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**Abstract:** This work presents the experimental study of several factors that influence the uncertainty of residual stress measurements using X-ray diffraction method. AISI 1070 steel sample was used to assess the influence of experimental and data analysis procedures (instrumental setup, geometry, data collection parameters, method of data processing and modeling) on the obtained values of residual stress. A comprehensive procedure of X-ray data treatment is demonstrated which together with the use of standard samples allows one to reduce significantly the scattering of residual stress values obtained in different experimental conditions.

**Key words:** residual stress, steels, X-ray diffraction.

## 1. INTRODUCTION

Residual stress is defined as a stress present in the sample in the absence of external load. All manufacturing processes introduce residual stress into mechanical parts which is of great technological importance for different industrial application fields such as aerospace, automotive, nuclear and microelectronics industries. The knowledge in the field of residual stress became especially important with the introduction of advanced multiphase materials like metal-matrix composites and coatings where thermal and mechanical incompatibilities of different phases originate residual stress. The modern approach to materials engineering, so-called prestress engineering approach, deals with the on purpose optimization of residual stress [1]. This allows one to exploit its beneficial effects, like an increase of the fatigue limit in the case of surface compressive stress, or to avoid its detrimental outcomes such as decreasing the stress corrosion behavior of a material in the case of tensile residual stress.

The basic component of the prestress engineering approach is the measurement technique of residual stress for materials quality control and processing analysis. Among various experimental methods of residual stress measurements developed over the last few decades X-ray diffraction is truly nondestructive technique which allows measuring elastic strain in polycrystalline materials from alterations in interplanar crystallographic distances induced directly by the existing residual stress. The triaxial stress tensor is then calculated using the applicable elastic constants of a material [2, 3].

Despite the relative straightforwardness, residual stress determination by X-ray diffraction method suffers from different sources of errors. From the experimental point of view, the sources of error can be separated in three categories: sample related uncertainties, statistical and systematic errors coming from measurement procedure and, finally, the uncertainties generated by data reduction process. This study will present a procedure of the residual stress determination in the sample of AISI 1070 steel that allows a correction for systematic errors. Such a procedure uses standard samples and X-ray data treatment within a framework of a fundamental parameter approach to diffraction pattern processing. We compare the results of the proposed procedure with the results of conventional approach to data treatment using commercially available software for different experimental conditions of X-ray data collection.

## 2. METHOD

### *2.1. Theoretical considerations*

The common basis of all lattice diffraction methods of residual stress analysis is the equation that relates the elastic strain of a particular family of crystallographic planes (*hkl*), so-called diffraction strain, to the components of a mechanical stress tensor [2, 3]:

$$\begin{aligned}\varepsilon_{\varphi,\psi}^{hkl} &= \frac{1}{2}S_2 \sin^2\psi \cdot \left[\sigma_{11}\cos\varphi + \sigma_{12}\sin(2\varphi) + \sigma_{22}\sin^2\varphi\right] + \\ &+ \frac{1}{2}S_2\left[\sigma_{13}\cos\varphi \cdot \sin(2\psi) + \sigma_{23}\sin\varphi \cdot \sin(2\varphi) + \sigma_{33}\cos^2\psi\right] + \\ &+ S_1(\sigma_{11}+\sigma_{22}+\sigma_{33}) = \frac{d_{\phi,\psi}^{hkl} - d_0^{hkl}}{d_0^{hkl}}\end{aligned} \quad (1)$$

The angles $\varphi$ and $\Psi$ identify the direction of the strain measurement, where $\Psi$ is the angle between the surface normal and the scattering vector, and $\varphi$ denotes the rotation of the sample around the surface normal (Fig. 1). The equation (1), known as $\sin^2\Psi$ law, derived for elastically isotropic samples, also holds for quasi-isotropic or microscopically elastically isotropic sample where no texture present and the grains interactions are isotropic. In the latter case, $S_1$ and $S_2$ are so-called *hkl*-dependent X-ray diffraction elastic constants. Equation (1) simplifies to

$$\varepsilon_{0,\psi}^{hkl} = \frac{1}{2}S_2 \cdot \sin^2\psi \cdot \sigma_{11} + S_1 \cdot (\sigma_{11}+\sigma_{22}) \quad (2)$$

for a plane state of stress when directions of principal stresses coincide with the sample coordinate system.

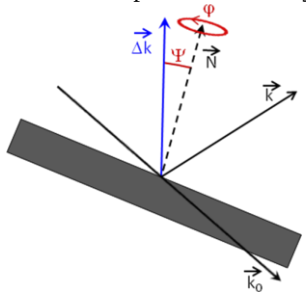


**Fig. 1. Definition of the angles $\varphi$ and $\Psi$**

At $\varphi=0$, one can determine the respective stress component from the slope of the measured strains plotted as a function of $\sin^2\Psi$.

### *2.2. Experimental procedures*

The investigated sample was made from heat treated AISI 1070 steel which microstructure consisted of homogeneous tempered martensite with a small amount of cementite. The small rectangular plate-like sample with the surface dimension of 20 by 23 mm was cut with electron discharge machining from a bigger plate subjected to a surface sand blasting treatment. The component $\sigma_{11}$ of the surface stress was determined with the help of equation (2) along the longer dimension of the sample surface.

The X-ray diffraction measurements were performed in two experimental geometries, **Ψ** (side inclination) and **Ω** (iso-inclination), with the use of Cr K$\alpha_1$ radiation, measuring (211) diffraction peak of sample´s martensitic structure. Different type of collimations of X-ray beam (1 mm circular, 0.5 mm circular and 0.6 x 1 mm rectangular) allowed for a variation of sample´s irradiated area. Several other factors like variation of 2Θ range of the measured Bragg peak and presence of Soller slits were also examined.

### *2.3. Results*

Figure 2 compares the linear regression lines obtain from the fit of experimental data to eq. (2) for different conditions of data collection using the conventional approach to data processing with software Stress V1.1. from Bruker-AXS.

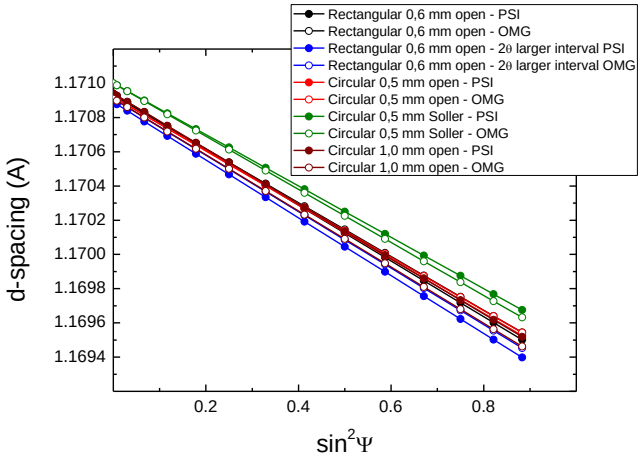


**Fig. 2. *D*-spacing of (*211*) reflection planes as a function of $\sin^2\Psi$**

Respective values of residual stress are compared in Fig. 3.

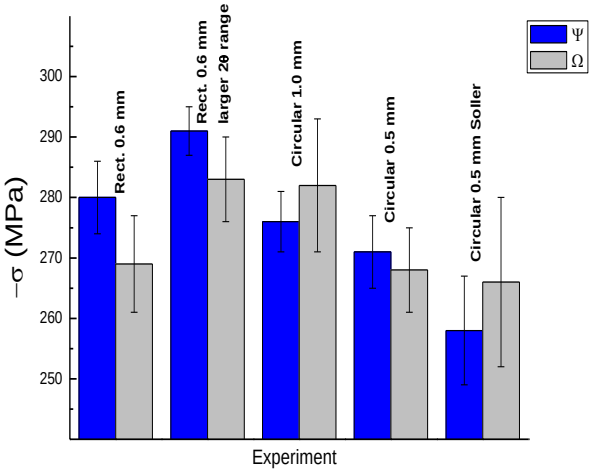


**Fig. 3. Residual stress obtained in different experimental conditions**

### *2.4. Discussion*

The uncertainty in residual stress values is defined mainly by the uncertainties in 2Θ of diffraction peak position and in strain-free *d*-spacing (equation 1). Relatively small alterations of experimental conditions used in this study induce noticeable scattering in the measured *d*-spacing and the resulting stress values (Figs. 2 and 3). Generally, all sources of errors can be classified between those leading to strain errors dependent on $\Psi$ and those leading to strain errors independent on $\Psi$. A complex interaction of error sources, difficulties to separate this interaction, besides the big number of parameters involved make it practically impossible to account for different experimental aberrations individually. The procedure that can deal with such a correction in overall way involves the use of standard materials and comprehensive data processing. The demonstration of such a procedure will be presented elsewhere.

## 3. CONCLUSION

The need of a procedure that accounts for experimental and data processing uncertainties in residual stress determination by X-ray diffraction technique is considered.

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