# Analysis of residual stresses

Anna Góral

## 1. Introduction

Residual stress is defined as the self-balancing stresses residing in a mechanical part in the absence of all externally applied forces and moments. Residual stress is encountered in the surface of practically every material. Residual stresses usually originate during manufacturing and processing of materials due to heterogeneous plastic deformations, thermal contractions and phase transformations. These residual stresses may have a significant effect on performance and lifetime. They combined with external load can be destructive or beneficial for the sample. The analysis of residual stress state is of great technological importance because it can improve or degrade the mechanical properties of material [1]. The effect of the stresses may be minor or can be catastrophic. Tensile stress which exceeds the elastic limit causes cracking in surface coatings, perpendicular to the direction of the tensile stress. In general, some degree of compressive stress is considered to be desirable as it closes surface cracks and improves fatigue properties. However, excessive compressive stress can cause cohesive failure, and adhesive failure in the case of coating [2]

Together with the microstructure and the texture, the stress state defines the material properties. A summary of the origins of residual stresses is given in Figure 1. It includes the residual stresses that arise from various mechanical treatments.

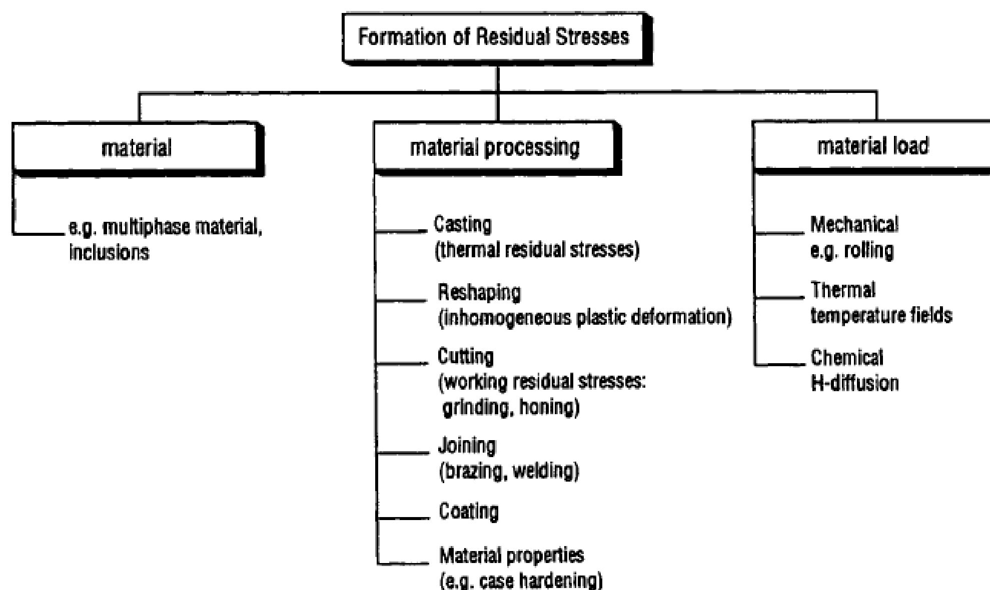


*Fig.1. Origin of residual – stress formation [3]*

## 2. Types of residual stresses

There are three types of residual stress [4]:

- ***Type I residual stresses*** *represent the average residual stresses acting within all phases and crystallites in the volume of the macroscopic material. These residual stresses result from long strain incompatibilities introduced, e.g., by strain or temperature gradients in a manufacturing process.*
- ***Type II residual stresses*** *describe the mean deviation from the macroscopic residual stress level of an individual crystallite (single phase material). These stresses vary on the scale on an individual grain; may be expected to exist in single phase materials because of anisotropy in the behavior of each grain, and in multi-phase materials as a result of the different properties of the different phases. Residual stresses type II arise for instance due to deformation misfits between neighboring grains and due to temperature or deformation induced misfits between the phases of a multiphase material.*
- ***Type III residual stresses*** *represent the local deviation of the residual stresses within an individual crystallite from its average residual stress (variation on the atomic scale). They exist within a grain, essentially as a result of the presence of dislocations and other crystalline defects. These stresses are caused, e.g., by void, solute atoms, or dislocations in the crystal lattice.*

The type I residual stresses are the most important from an engineering point of view, while the remainder is of interest in materials science studies.

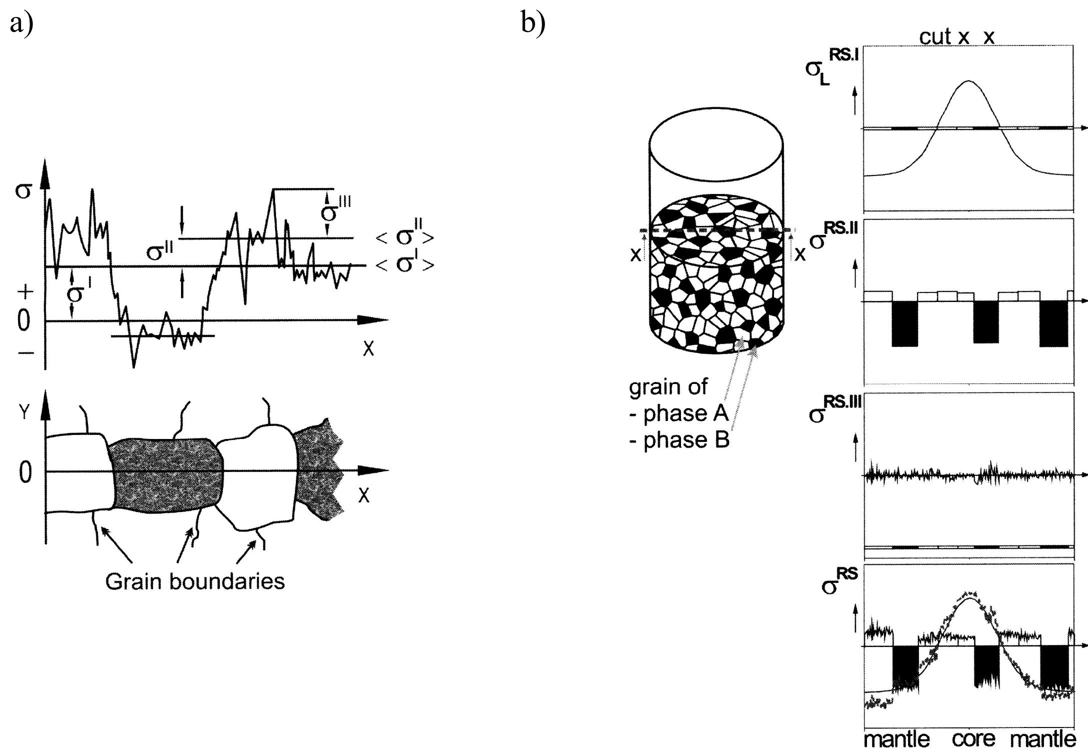


*Fig.2. Definition of type I, type II, and type III residual stresses in single phase material (a) and multiphase material [4]*

## 3. Methods of residual stress determination

Many methods of the residual stress measurement have been developed over the last few decades, both destructive and non-destructive in nature. Residual stress measurement techniques can be divided into three categories: diffraction methods, mechanical methods and others [5].

### 3.1. Diffraction Methods

Diffraction methods of the residual stress measurement are considered as a non-destructive.

#### *3.1.1. The X-ray diffraction method*

The residual stress determined using x-ray diffraction is the arithmetic average stress in a volume of material defined by the irradiated area, and the depth of penetration of the x-ray beam. The linear absorption coefficient of the material for the radiation used governs the depth of penetration.

Diffraction methods of residual stress determination basically measure the angles at which the maximum diffracted intensity take place when a crystalline sample is subjected to X-rays. From these angles it is possible to obtain the interplanar spacing of the diffraction planes using Bragg's law:

$$2d_{hkl} \cdot \sin \theta_{hkl} = \lambda$$

where $\lambda$ is the wavelength of the radiation, $d_{hkl}$ is the lattice plane spacing of a family of crystallographic planes (*hkl*) responsible for the Bragg peak and $\theta_{hkl}$ is the angular position of this diffraction peak.

If the residual stresses exist within the sample, then the d spacing will be different than that of an unstressed state. This difference is proportional to magnitude of the residual stress. The traditional XRD method for residual stress measurement is known as the $\sin^2\psi$ method, which is based on the measurement of the shift of a diffraction peak position recorded for different $\psi$ angles [1,3]. In this approach, a specific diffraction plane is selected and the interplanar spacing is measured from a coupled $\theta$–$2\theta$ scan (standard Bragg–Brentano (B-B) geometry) of the specimen at different specimen tilt angle $\psi$ - the angle between the diffracting plane normal and the specimen surface normal. Ideally, a high-$2\theta$ diffraction peak is chosen to ensure higher sensitivity to strain. The residual strain can be derived from the slope of a linear plot between the fractional change of the plane spacing (i.e. strain) and $\sin^2\psi$. In most cases a bi-axial stress model is then used to convert the strain measured to the stress. The traditional residual stress measurements using symmetric B-B geometry are unsuitable for highly textured thin-film specimens.

Because the x-ray penetration is extremely shallow ($< 10$ μm), a condition of plane-stress is assumed to exist in the diffracting surface layer. The stress distribution is then described by principal stresses $\sigma_{11}$, and $\sigma_{22}$ in the plane of the surface, with no stress acting perpendicular to the free surface, shown in Figure 3. The normal component $\sigma_{33}$ and the shear stresses $\sigma_{13} = \sigma_{31}$ and $\sigma_{23} = \sigma_{32}$ acting out of the plane of the sample surface are zero. A strain component perpendicular to the surface, $\varepsilon_{33}$, exists as a result of the Poisson's ratio contractions caused by the two principal stresses [6].

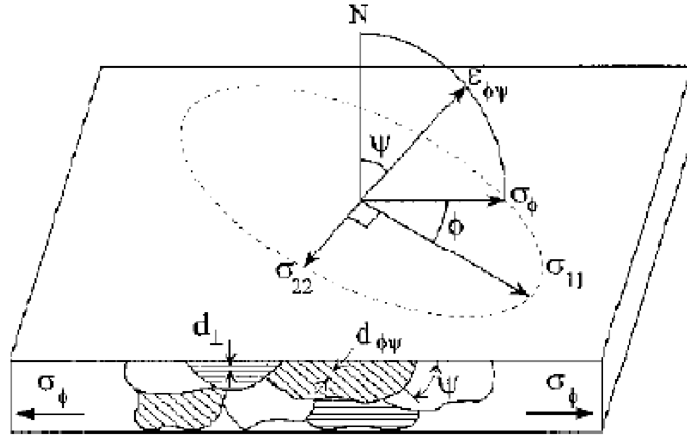


*Fig.3. Plane stress at free surface showing the change in lattice spacing with tilt $\psi$ for a uniaxial stress $\sigma_\phi$ parallel to one edge [6]*

The strain in the sample surface at an angle $\phi$ from the principal stress $\sigma_{11}$ is then given by:

$$\varepsilon_{\phi\psi} = \left(\frac{1+\nu}{E}\right)\sigma_\phi \sin^2\psi - \left(\frac{\nu}{E}\right)(\sigma_{11}+\sigma_{22})$$

Equation 1 relates the surface stress $\sigma_\phi$, in any direction defined by the angle $\phi$, to the strain, $\varepsilon_{\phi\psi}$, in the direction $(\phi,\psi)$ and the principal stresses in the surface. If $d_{\phi\psi}$ is the spacing between the lattice planes measured in the direction defined by $\phi$ and $\psi$, the strain can be expressed in terms of changes in the spacing of the crystal lattice:

$$\varepsilon_{\phi\psi} = \frac{\Delta d}{d_0} = \frac{d_{\phi\psi} - d_0}{d_0}$$

where $d_0$ is the stress-free lattice spacing. Substituting into $\varepsilon_{\phi\psi}$ and solving for $d_{\phi\psi}$ yields:

$$d_{\phi\psi} = \left[\left(\frac{1+\nu}{E}\right)_{(hkl)} \sigma_\phi d_0\right]\sin^2\psi - \left(\frac{\nu}{E}\right)_{(hkl)} d_0(\sigma_{11}+\sigma_{22}) + d_0$$

This equation is the fundamental relationship between lattice spacing and the biaxial stresses in the surface of the sample.

The lattice spacing $d_{\phi\psi}$, is a linear function of $\sin^2\psi$. The oscillatory d vs. $\sin^2\psi$ behavior indicates the presence of inhomogeneous stress distribution.

In standard $\sin^2\psi$ method the region of measurement is not strictly determined because the irradiated volume changes during the measurement. Therefore, for a stress measurement in the near-surface coatings the ***grazing-incidence X-ray diffraction (g-sin$^2\psi$) method*** – GIXD is very popular [7-9]. Grazing-incidence diffraction enables to determine the stresses at strict penetration depth by choosing narrow angles of incidence in asymmetric detector setup. The GIXD method for stress analysis is useful in two cases: (i) to restrict the effective penetration depth to a defined small value when the stress state close to the surface of a body has to be determined or when stress analyses have to be performed for very thin films for which problems of overlap with substrate peaks can occur; (ii) to determine stress gradients from diffraction measurements at different effective penetration depths by varying the angle of incidence or the wavelength [9]. However, g-$\sin^2\psi$ method guarantees constancy of X-ray penetration into investigated material only for few possible depths from surface.

### *3.1.2. Neutron diffraction*

Neutron diffraction measures strain components from changes in crystal lattice spacing. Neutrons have the advantage over X-rays that for wavelengths comparable to the atomic spacing, their penetration into engineering materials is typically many centimetres. There are essentially two neutron diffraction techniques: conventional $\theta/2\theta$ scanning and time of flight approaches. In general, continuous sources tend to offer the best performance when a small region of the whole diffraction profile is required (e.g. single peak based measurements of the macrostress), while time of flight instruments are especially good in situations where a number of peaks, or the whole diffraction profile, is required (e.g. for multiphase materials or where large intergranular strains are to be expected) [5].

### *3.1.3. Synchrotron diffraction*

Synchrotrons (hard X-rays), provide very intense beams of high energy X-rays. These X-rays have higher depth penetration than conventional X-rays. This increased penetration depth means that synchrotron diffraction is capable of providing high spatial resolution, three-dimensional maps of the strain distribution to millimetre depths in engineered components. Higher penetration depth is considered as one of the major advantages of synchrotron diffraction over the conventional X-ray diffraction.

## **3.2. Mechanical stress measurement methods**

These methods based on the monitoring of changes in component distortion, either during the generation of the residual stress, or afterwards, by deliberately removing material to allow the stress to relax [5].

### *3.2.1. Curvature*

These methods are usually used to determine the stress within coatings and layers. The deposition of a layer can induce stresses which cause the substrate to curve. The changes in curvature during deposition make it possible to calculate variations in stress as a function of deposit thickness. Curvature can be measured using contact methods (e.g. profilometry, strain gauges) or without direct contact (e.g. video, laser scanning, grids), allowing curvatures down to about 0.1 $mm^{-1}$ to be routinely characterised.

### *3.2.2. Hole drilling*

The undisturbed portions of a stressed sample will relax into a different shape when the locality is machined; this provides data for the calculation of residual stress.
The hole-drilling method relies on stress relaxation when a hole is drilled into the center of a rosette strain gage. When the material is removed by drilling, the extent of the strain relief is monitored by the gages and the direction and magnitude of the principal stresses can be calculated.

### *3.2.3. Compliance methods*

The crack compliance method is basically cutting a small slot to see the relaxation of stress in the vicinity of the crack using strain gauge interferometry. Increasing the depth of the slot will allow resolving the stress field normal to the crack as a function of depth for relatively simple stress distributions.

### 3.3. Other methods

#### *3.3.1. Magnetic and electrical methods*

There are two magnetic methods: the magnetostriction and the Barkhausen noise. If magnetostrictive materials are stressed the preferred domain orientations are altered, causing domains most nearly oriented to a tensile stress to grow (positive magnetostriction) or shrink (negative magnetostriction). Stress induced magnetic anisotropy causes the rotation of an induced magnetic field away from the applied direction. When the assembly is rotated, both the principal stress directions and the size of the principal stress difference can be measured. *Magnetoacoustic 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 emf proportional to the rate of change in magnetic moment detected in probe coils as domain walls move. Magnetic methods have the advantage of providing cheap and portable methods for non-destructive residual stress measurement [5].

#### *3.3.2. Ultrasonic methods*

Changes in ultrasonic speed can be observed when a material is subjected to a stress, the changes providing a measure of the stress averaged along the wave path.
The greatest sensitivity is obtained when the wave propagates in the same direction as the stress. The method provides a measure of the macrostresses over large volumes of material.

#### *3.3.3. Piezospectroscopic effects*

Characteristic Raman or fluorescence luminescence lines shift linearly with variations in the hydrostatic stress. These methods are well suited to the study of fibre composites, providing basic information about the build up of stresses from fibre ends to centres and to distinguish between micro- and macrostresses.

#### *3.3.4. Thermoelastic methods*

The elastic deformations in the materials cause small changes in temperature (1 mK for 1 MPa in steel). It is possible to map the thermal variations using an infrared camera. These variations are indications of variations in stress. Using the thermoelastic constant describing the dependence of temperature on stress the hydrostatic stress component can be determined. This method is usually used in fatigue studies.

#### *3.3.5. Photoelastic methods*

The speed of light is prone to vary anisotropically in transparent materials, when the material is subjected to stress. This tendency is called photoelastic effect. It gives rise to interference fringe patterns when such objects are observed in white or monochromatic light between crossed polars. It is possible to interpret the resulting fringe patterns to give the local maximum shear stress.

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