MACROSCOPIC RESIDUAL STRESSES IN STEELS GROUND UNDER VARIOUS CONDITIONS OF HEAT REMOVAL

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Macroscopic residual stresses on the surface and their depth distributions in steels ground in various cooling environments represent the central issue of this contribution. The specimens were manufactured from three ferrous materials – carbon steel C45, low carbon Mn-Cr steel 16MnCr5 and corrosion-resistant chromium steel M300, and consequently ground with face grinding machine and corundum wheel in three regimes of heat removal: ambient air, emulsion of water and synthetic fluid for grinding operations and cooling air from Ranque –Hilsch vortex tube. Methods of X-ray diffraction (XRD) analysis were applied for evaluation of anisotropic state of triaxial residual stress. Since the XRD is sensitive to surface layers of only a few micrometers in thickness, electro-chemical etching had to be employed in order to obtain gradients of chosen components of macroscopic residual stress tensor.

Keywords

grinding, cooling, residual stress, X-ray diffraction, electro-chemical polishing

1. Introduction

Experimental stress analysis by the means of X-ray diffraction (XRD) epitomises a palpable example of relationship between Angström-scaled atom physics and centimetre- or meter-scaled mechanics. The wavelengths of used X-rays are of the same order of magnitude as interatomic spacings in crystal lattice which makes it possible to measure them and, consequently, even detect some types of their deviations. Both residual and load stresses can be counted to such deviations because elastic stresses in a volume element of a solid-state body are reflected by displacements of atoms from their equilibrium positions. Therefore, diffracted X-ray beam inherently contains information about strains in the irradiated volume. Eventually, elasticity equations allow us to compute stresses from the measured strains. It should be vigorously emphasized that only a complete, second order, symmetric tensor (i. e., comprising of $3^2 = 9$ components out of which only 6 are necessary to pinpoint because of the symmetry) is the correct representation of RSs.

Perfectly homogenous and isotropic materials which underwent a homogeneous and isotropic deformation are virtually nonexistent and, therefore, residual stresses exist. It has been shown [Youtsos 2006] that, in general, compressive residual stresses (RSs) in the material can favourably reinforce the dynamic strength by about 50 per cent; on the other hand, tensile RSs could reduce the dynamic strength by about 30 per cent. Such favourable effect of compressive RSs can be derived from mechanical model of counterbalancing, when the RSs mitigate the adverse effects of tensile load stresses [Abu-Nabah 2007] that occur during the service. Both theoretical and experimental determination of residual stresses distribution in a component is therefore important for assessment of their quality and possible reactions to external loads during the service. The theoretical part most commonly consists in finite element modelling of processes of inhomogeneous plastic and thermal deformation, the result is ideally a three dimensional picture of residual stress fields [Halama 2008]. Even though the models are indeed needed, they are usually compared with data from experimental determination of residual stresses.

There exists an array of techniques aimed at measuring residual stresses exploiting various physical principles ranging from stress relaxation during a hole creation to change in lattice parameters due to the present elastic stresses. The presented paper deals with residual stress analysis by means of X-ray diffraction technique which is capable of whole stress tensor determination and it even facilitates simultaneous evaluation of macroscopic (or first-order) and microscopic (second order) residual stresses from diffraction patterns. Measurement of residual stresses by X-ray diffraction has soaring tendency over the last twenty years because of significant development in the X-ray diffraction measuring equipment including construction of synchrotrons as sources of tunable X-ray radiation of high intensity.

Grinding is a mechanical surface treatment that causes inhomogeneous plastic deformation in the near-surface area resulting in RS due to the greater relaxation of this region compared to the bulk. The mechanical interaction between the grinding wheel and the workpiece is also responsible for the increase of temperature in the area where friction takes place. A part of the emergent heat is conducted into the material and, taking into account inhomogeneous temperature fields, the thermal stresses arise consequently. The creation of heat may even lead to thermal damage to the workpiece, which may severely reduce its fatigue and wear life. Various cooling techniques are applied in order to conduct the heat away from surface, and, thus, subdue tensile stress generation.

Effective penetration depth of primary X-ray beam into ferrous material is several micrometers and hence subsequent surface layer removal must be performed in order to obtain depth distribution of residual stress. This is usually done by means of electro-chemical etching. During electro-chemical polishing the process of anodic dissolution takes place. The anode is formed by the sample itself. The product of this process is a solution with high electrical resistance which is embedded into microscopic wells in the sample surface and preferential removal of roughness proceeds [Pala 2008].

2. Experimental

The squared samples 50 mm in dimensions were 5.5 mm thick and made from mild carbon steel C45 (CSN 12 050), low carbon Mn-Cr steel 16MnCr5(CSN 14 220), and from corrosion-resistant chromium steel M300 [Fürbacher 2007]. All samples were first annealed at 550 °C in argon atmosphere for 2 hours; the decline of temperature after annealing was gradual in order to rule out any additional thermal stresses. The finish surface grinding was conducted on the face grinding machine BPH 320 A with corundum grinding wheel. The samples were fixed on magnetic table, which was translating in respect to the grinding wheel rotation axis, and, hence, enabling the alternating processes of down-cut and up-cut grinding. The grinding conditions were as follows: the wheel speed – 35 m/s, tangential speed of table drift – 10 m/min, axial table drift – 1 mm per stroke, and thickness of removed layer – 0.02 mm. The grinding wheel was trued up after each sample in order to maintain constant grinding conditions. In the experiment, emulsion of water and synthetic fluid *Cimtech A31F* for machining operation was used as a cooling liquid; the amount of incoming liquid being 5 l per minute. The source of cooling air with temperature of −28 °C was a Ranque-Hilsch vortex tube [Gao 2005]. For comparison, one sample was ground without any cooling.

Ground samples were investigated for RSs on the surface by XRD and, subsequently, surface layers were being successively removed by the process of anodic dissolution which took place during electrochemical polishing. In-between polishing processes, the RSs were determined so that depth distribution of both normal and shear components of macroscopic stress tensor could be found.

3. X-ray diffraction stress analysis

Stress analysis was performed by using Dölle – Hauk method, which is sometimes called *modified* sin^2 ψ *method* [Hauk 1997], and offers the possibility of computation of the complete stress tensor provided that the XRD measurements were carried out in three azimuths φ (most frequently 0°, 45°, 90° with respect to the grinding direction) and for both positive and negative tilts ψ, see Fig. 1. This method is suitable for evaluation of the most general anisotropic triaxial state of residual stress which is of vital importance for ground surfaces that exhibit the so-called ψ splitting [Dölle 1980] in the grinding direction. Oftentimes discussed issue in the algorithm of stress tensor computation are the X-ray elastic constants (XEC), which were in our case taken from the tables [Kraus 1995], where the Eshelby – Kröner model was used for their calculation.

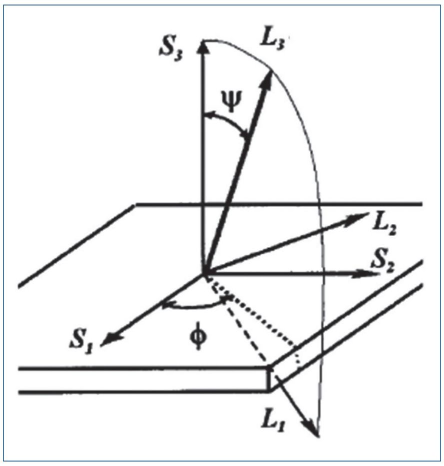

Figure 1. *Coordinate systém of the sample S and laboratory L with depiction of tilt ψ and azimuth φ [Hauk 1997].*

For surface layer removal the LectroPol-5 by Struers, an apparatus for automatic, micro-processor controlled electrolytic polishing and etching of metallographic specimens, was used. The removed, circular-shaped area 10 mm in diameter was in the middle of the surface. For further X-ray diffraction measurements, the sample was sheltered by a nondiffracting plastic covering with a square-shaped hole of 5×5 mm².

Upon contemplating the process of repetitive layer removals, a question might arise about a necessity of correction to relaxation or, to be more precise, redistribution or RSs. Such correction model was rigorously elicited by Moore & Evans [Sikarskie 1967] for biaxial state of RS and its application to more general case of triaxial state of RS would be, therefore, inconsistent.

4. Results

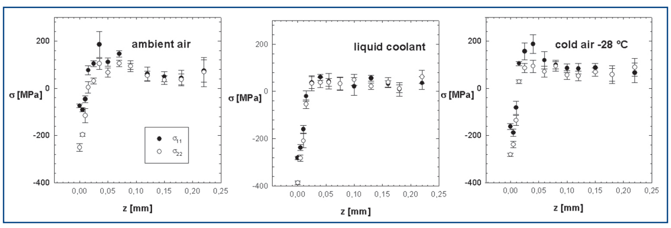

Figure 1. *Distribution of RSs σ11 (in the grinding direction) and σ 22 (perpendicular to grinding) in surface layers of mild carbon steel C45*

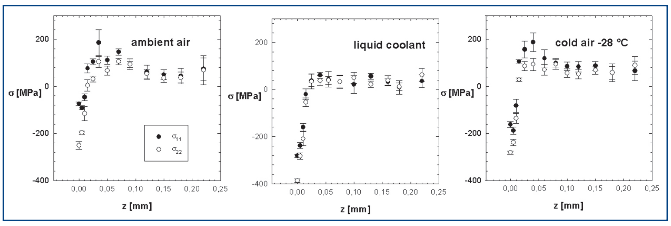

Figure 2. *Distribution of RSs σ11 and σ22 in surface layers of low carbon steel 16MnCr5*

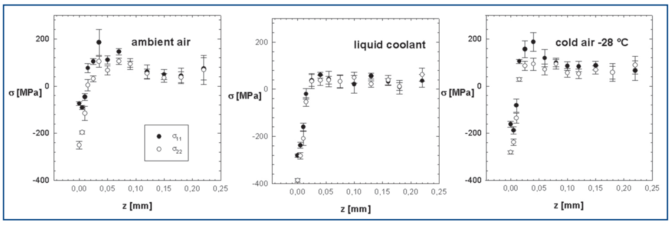

Figure 3. *Distribution of RSs σ11 and σ22 in surface layers of corrosion-resistant steel M300*

5. Conclusions

XRD analysis of surface residual stresses and their depth distribution (Figs. 1 -3) in ground steels C45, 16MnCr5 and M300 by means of Dölle – Hauk method proved that form of heat removal from the grinding zone has following impacts on RSs:

- in all studied surfaces (i. e., before polishing) $|\sigma_{22}| > |\sigma_{11}|$ and σ_{22} was always compressive, which is due to the anisotropic character of the grinding process,
- surface RS in samples made from C45 and M300 steels are the lowest (in mathematical sense) for liquid cooling,
- the normal stresses σ_{11} and σ_{22} become equal to each other (within the experimental inaccuracy) approximately in a depth of 50 μm; the only exception being sample made from M300 steel and cooled by liquid,
- maximum of the RSs depth distribution in the case of liquid cooling is clearly the lowest for C45 steel and the highest for M300 steel, the influence of chemical composition (M300 contains about 13 % of chromium) is most likely the source of the observed behaviour,
- RS depth distribution in 16MnCr5 steel does not vary significantly with the cooling method from the point of view of maximum in the distribution, yet the gradient of RSs is the lowest in the sample cooled by liquid.

Acknowledgements

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