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

MAKROSKOPICKÁ ZBYTKOVÁ NAPĚTÍ V OCELÍCH, BROUŠENÝCH PŘI RŮZNÝCH PODMÍNKÁCH ODVODU TEPLA

Abstract

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.

Abstrakt

Příspěvek se zabývá vlivem způsobu odvodu tepla při rovinném broušení ocelí na stav povrchové makroskopické zbytkové napjatosti i distribuce zbytkových napětí do hloubky. Laboratorní vzorky byly zhotoveny ze tří materiálů – uhlíkové jakostní oceli *C45*, mangano-chromové oceli *16MnCr5* a korozivzdorné chromové oceli *M300*, a následně rovinně broušeny korundovým kotoučem na sucho, při použití speciální emulze určené pro brousící procesy a při chlazení vzduchem různých teplot z Ranqueho – Hilschovy vírové trubice. Experimentálně zjištěný anizotropní stav trojosé napjatosti byl zkoumán metodami rentgenové difrakční tenzometrie, které byly z důvodů své povrchové povahy doplněny o elektro-chemické leštění pro studium gradientů jednotlivých složek tenzorů makroskopické zbytkové napjatosti.

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

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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.

Perfectly homogenous and isotropic materials which underwent a homogeneous and isotropic deformation are very rare and, therefore, residual stresses exist. It has been shown [1] 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 [2] that occur during the service.

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.

2 EXPERIMENTAL

The squared samples 50 mm in dimensions were 5.5 mm thick and made from mild carbon steel *C45* (*ČSN 12 050*) [3], low carbon Mn-Cr steel *16MnCr5*(*ČSN 14 220*), and from corrosion-resistant chromium steel *M300* [4]. 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 [5]. 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 electro-chemical 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* $sin^2\psi$ *method* [6], 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. This method is suitable for evaluation of the most general anisotropic trialxial state of residual stress which is of vital importance for ground surfaces that exhibit the so called ψ splitting [7] 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 [8], where the Eshelby – Kröner model was used for their calculation.

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 [9] for biaxial state of RS and its application to more general cases would be, therefore, inconsistent.

4 RESULTS

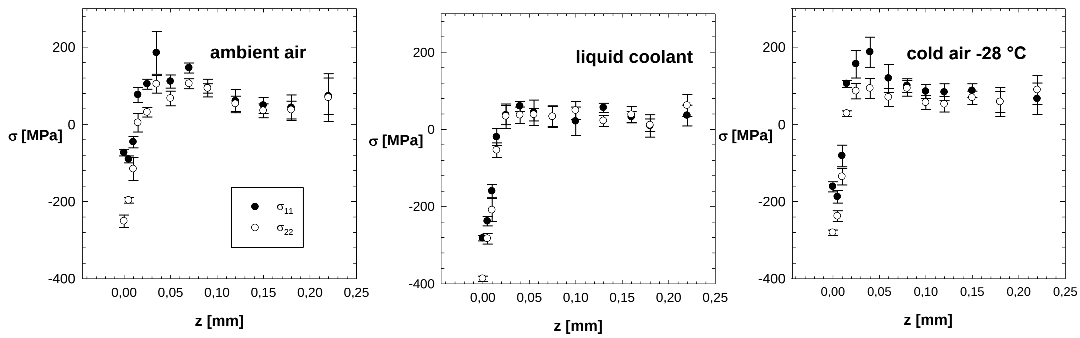

Fig. 1 Distribution of RSs σ_{11} (in the grinding direction) and σ_{22} (perpendicular to grinding) in surface layers of mild carbon steel *C45*

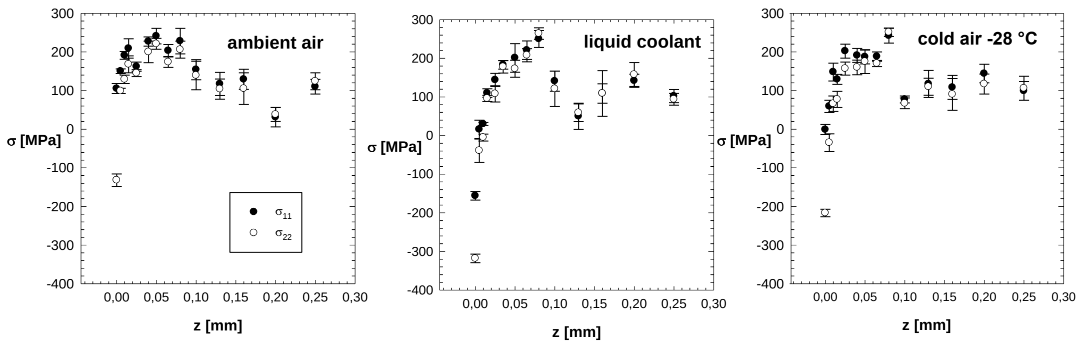

Fig. 2 Distribution of RSs σ_{11} and σ_{22} in surface layers of low carbon steel *16MnCr5*

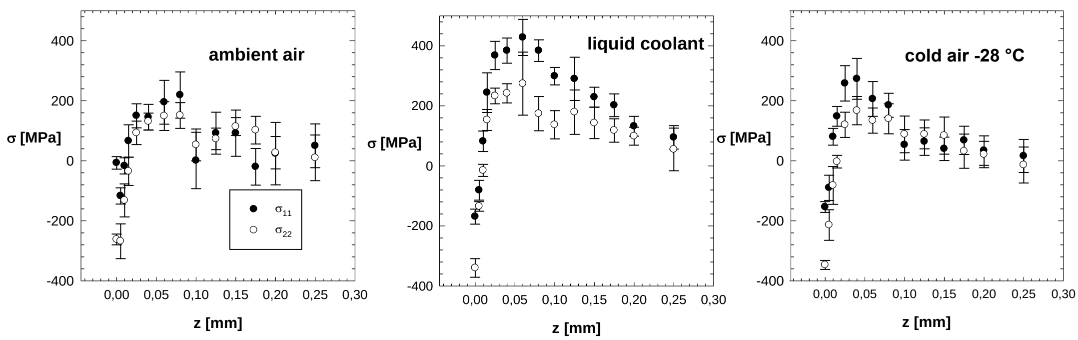

Fig. 3 Distribution of RSs σ_{11} and σ_{22} in surface layers of corrosion-resistant steel *M300*

3 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.

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