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Residual Stress Depth Profile in Surface Layers of Shot-Peened Decarburised Steels

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Abstract: Surface decarburization of construction steels occurs during their forging, drawing and casting. As a softening process, decarburization leads to a considerable fatigue limit decrease. This detrimental effect can be reduced by strengthening the decarburised layer using plastic deformation induced by shot peening. As a result compressive residual stresses are created in the surface layer.

The aim of the contribution is to present the results of X-ray diffraction analysis of residual stress depth profiles in surface layers of sand-blasted and shot-blasted steels. Depth distributions of macroscopic (first-order) residual stresses were determined up to approx. 500 μm beneath the blasted surface.

Keywords: steels, shot peening, residual stresses, X-ray diffraction, decarburization

1. Introduction

Decarburization, the kinetic process in which carbon diffuses from the surface of a metal (typically steel), weakens the surface layer of the specimen since the hardness, i.e. strength, of a steel is dependent mainly on the carbon content and phases present [1]. Common high temperature technological processes of steel and cast iron semi-products like casting, working (forging, rolling, etc.) and any other heat treatment without protective atmosphere are susceptible to decarburization [2]. It has been known for a long time that the process of decarburization leads to harmful effects if not dealt with through a secondary process by strengthening the decarburised layer using plastic deformation induced by, e. g. shot peening. As a result compressive residual stresses are created in the surface layer. There is no analytical technique which allows us to evaluate such non-uniform stress fields as efficiently as X-ray diffraction.

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2. Samples investigated and experimental techniques

Five squared samples 50 × 50 × 3 mm^3 from the steel of Czech grade 12 020.1 subjected to various blasting conditions were investigated. The effect of sandblasting was caused by using SiO_2 sand with grain size of 0.5 – 0. 7 mm in diameter. Granulated steel of particles 0.6 – 0.8mm in diameter (hardness 40 – 55 HRC) was blasted onto samples with three different pressure levels and total amounts of particles – see Table 1.

Table 1. Working conditions for investigated surfaces.

sample	cutting operation	pressure, MPa	total mass of particles, kg
AR	as received	---	---
0.5-0.5	sand-blasted	0.5	0.5
4-8	shot-blasted	0.4	4
8-8	shot-blasted	0.8	8
8-12	shot-blasted	1.2	8

The residual stress measurements were performed with a θ - θ *X'Pert PRO* diffractometer in ω-arrangement with *CrKα* radiation. The line *{211}* of *α-Fe* phase was measured. Nine different tilts angles (ψ) from 0° to 63° were used. The $sin^2\psi$ method was applied for determination of macroscopic residual stress [3]. The X-ray elastic constants ½ $s_2 = 5.95 \cdot 10^{-6}$ MPa^{-1}, – $s_1 = 1.325 \cdot 10^{-6}$ MPa^{-1} were used in stress calculations. The single line Voigt function method [4] was applied for corrections of instrumental broadening and determination of crystallite size *D*. In order to analyse the stress gradients beneath the samples surface the layers of material were gradually removed by electrolytic polishing.

The surface roughness was measured by laboratory tester *MITUTOYO SURFTEST 2000*. The arithmetical mean surface roughness of measured profile *Ra* was evaluated.

3. Results and their discussion

The back-reflection X-ray diffraction patterns, taken before performing residual stress measurements, correspond to diffraction of the spectral doublet $CrK\alpha_1\alpha_2$ on crystallographic planes *{211} α-Fe* (see Fig. 3) While the surface shows isotropic fine-grained polycrystalline structure with plastic deformation (the diffraction line is broad, continuous, and has homogeneous intensity around its perimeter), in the case of the removed 0.2 mm layer, the diffraction line becomes narrow with a slight indication of discrete diffraction spots located uniformly around perimeter, i.e. without any sign of texture. This is the reason why the samples can be used for determination of the surface residual stress by X-ray tensometry.

The Table 2 contains results of surface residual stress measurements (σ_L, σ_T) performed in two mutually perpendicular directions, the breadth *W {211} α-Fe* diffraction line, and the arithmetical mean surface roughness of measured profile *Ra*.

Table 2. Values of surface macroscopic residual stresses σ_L, σ_T and breadth W of *{211} α-Fe* diffraction line determined on all the investigated surfaces.

sample	σ_L, MPa	σ_T, MPa	<*W*>, deg	*Ra*, μm
AR	-31±3	-37±3	1.413	3.82±0.72
0.5-5	-370±6	---	2.648	3.20±0.98
4-8	-338±5	-347±9	2.507	2.65±0.79
8-8	-270±6	-286±8	2.635	3.84±1.06
8-12	-175±5	-186±10	2.780	4.33±0.92

The inaccuracy (experimental error) of W is approx. 0.05 °2θ. The quantity W could be considered to be a mean degree of plastic deformation in the irradiated volume of material.

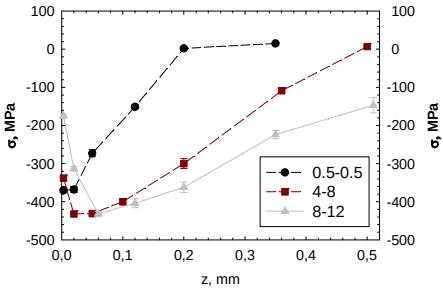

Fig. 1. The depth profiles of macroscopic stresses in surface layers of investigated samples.

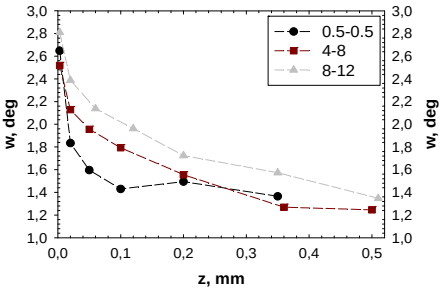

Fig. 2. The distributions of width of *{211} α-Fe* diffraction line beneath the blasted surfaces.

It is evident that surface values of residual stresses (see Table 2) are not able to represent the essence of the process of interaction of blasting particles with the worked material. For this reason, depth profiles of monitored values σ and W were determined (Fig. 1, Fig. 2). The crystallite size D depth profiles (Fig. 4) calculated from the *{211} α-Fe* diffraction lines according to [4] give additional information about the influence of blasting on the real structure of the samples under investigation.

4. Main conclusions

The essential conclusions that can be derived from the performed analyses are listed below:

- On the surface of all the investigated samples was identified isotropic two-dimensional state of favourable compressive residual stresses, i. e. $\sigma_L \approx \sigma_T$. The highest value (– 370 MPa) was found on the sand-blasted surface.
- The lowest values of residual stresses and diffraction line width are in the case of the as-received sample.

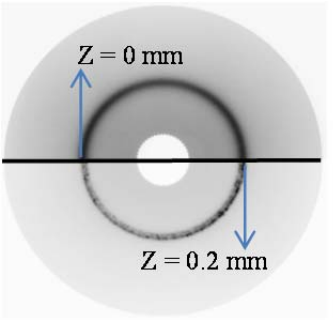

Fig. 3. Back-reflection X-ray diffraction patterns from the surface (z = 0 mm) and after removing a layer of the thickness 0.2 mm of the sample *0.5-0.5*.

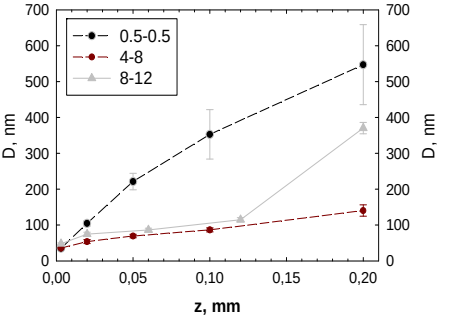

Fig. 4. The depth profiles´ courses of crystallite size D determined from the *α-Fe {211}* line profiles.

- The increase of air pressure leads to a decrease (relaxation) of the surface compressive stresses, and in the same time diffraction line width W increases, which indicates the higher degree of plastic deformation.
- The roughness parameter *Ra* (see Table 2) at the beginning declines with the total blasting intensity – the original surface becomes smoother – up to the sample *8-8*, and then again increases since the high velocity (energy) particles brings about new pits in the surface.
- The depth profiles of residual stresses reflect the different intensity of blasting particles. Since the stress influenced depth of the sandblasted sample *0.5-0.5* is only 0.2 mm (see Fig. 3), in the case of the rest two samples the compressively prestressed layer is deeper than 0.5 mm. The crystallite size D profiles (Fig. 4) correlate with the stress distributions.

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