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Surface layer characterisation of bearing rings

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ABSTRACT

Purpose: The X-ray quantitative phase analysis was used to establish volume fraction of transformed retained austenite. Theoretical calculation of residual macro-stresses due to volume fraction of transformed austenite in bearing rings and following measurements of residual stresses were carried out as well. The bearing elements were made of 100Cr6 steel and they were smoothed and grinded.

Design/methodology/approach: Particular features of diffraction patterns like angle position; shape and intensity are used to characterize phase composition, residual micro and macro-stresses, crystallographic texture, lattice parameter, defects density and crystalline size.

Findings: Machining by micro-deformation causes microstructural changes i.e. mechanically induced phase transformation of retained austenite and residual macrostresses. E.g. grinding cased tension and small compression whereas the mechanical smoothing of bearing rings caused high compresive residual stresses about -713 MPa.

Research limitations/implications: For precise interpretation of differences between following results needs another investigations: i.e. measurement of retained austenite and residual stresses in rings after heat treatment before any mechanical treatment.

Practical implications: The non-destructive character and large number of structural informations contained in diffraction pattern are the beneficial feature of diffraction methods. Therefore they have potential ability in application to technological operations and to diagnostic during fatigue.

Originality/value: The non-destructive structure characterisation of surface layers for various kinds of bearing rings can be powerful method in surface characterization and in quality control. This results contribute in general relations between microstructure and properties.

Keywords: Surface layers; Bearing rings; Retained austenite; Residual macroscopic stresses

METHODOLOGY OF RESEARCH, ANALYSIS AND MODELLING

1. Introduction

Random kind of treatments (mechanical, thermal or thermo-mechanical) are frequently used in surface finishing and strengthening of bearing elements. They effectively generate and/or release residual stresses. The residual stresses are thermally activated by thermal stress field energy and diffusion processes by slip and climb dislocation, generation and annihilation of lattice defect and phase transition of austenite. The heat treatment accompanies physical phenomena and additional surface mechanical treatment are main factors in creating stresses. A long time annealing, slowly heating or cooling cause relaxation of residual stresses. Cyclic mechanical loading also possibly contribute to relaxation of residual stresses.

The increase of specific volume ($\Delta V/V = k_{\alpha\gamma}$) due to martensite phase transition $Fe_\gamma \rightarrow Fe_\alpha$ in steel depends on carbon content (% wt. C) and the strain may be determined by empirical relationship [1].

$$\frac{\Delta V}{V(293K)} = 3.216 + 0.859 \cdot \%wt.C - 0.343 \cdot (\%wt.C)^2 [\%]. \quad (1)$$

Final quantity of crystal lattice strain generated by residual stresses (σ_I), which compensates phase transition strains is described by relations proposed by Greenwood–Johnson [2].

$$\varepsilon_{\sigma,transf} = \frac{5}{6}\frac{\sigma_I}{R_e}\frac{\Delta V}{V} \tag{2a}$$

$$\sigma_I = \frac{6}{5}\frac{R_e \cdot \varepsilon_{\sigma,transf} \cdot V}{\Delta V} \tag{2b}$$

Relative volume change of surface layer comparatively to bulk of material represents volume strain ($\varepsilon_{\Delta V}$) which depends on amount of retained austenite (w_{AS}), on fraction of transformed austenite (k_I) and can be evaluated according to [3,10]:

$$\varepsilon_{\Delta V} = k_1 \cdot w_{AS} \cdot k_{\alpha/\gamma} V_p^{-1}. \tag{3}$$

When flat (surface) state of stresses is assumed, residual stress can be calculated by using linear strain ($\varepsilon_{x,\Delta V}$):

$$\sigma_x = \sigma_y = \frac{\varepsilon_{x,\Delta V} E}{1-\nu}. \tag{4}$$

In majority of cases above calculations can be applied only for preliminary estimation of residual stresses. Therefore measurement of these stresses is usually final proof solution. Most commonly X-ray diffraction quantitative phase analysis method of austenite in steel is direct comparison method in which diffraction patterns for austenite and martensite (ferrite) are used [4,5]. The residual stresses in surface layers of bearings rings were measured by modified $sin^2\psi$ method [3,6].

2. Description of the methodology, materials for research, experiments

2.1. Samples and X-ray diffraction patterns

The samples were in form of rings. Samples were as final products in form of bearing elements with different internal diameter made of 100Cr6 steel.

This rings were prepared with different methods in goal of specific surface and surface layer properties. These applied approaches were as following: smoothing and mechanical grinding and burnishing.

The applied mechanical treatment consisted of grinding and in second variant additionally smoothing.

This different production methods resulted in different properties of surface layer e.g. retained austenite volume fraction, residual stresses and hardness.

Diffraction patterns were recorded with BRUKER D8-Advanced diffractometer using filtered $Co_{K\alpha}$ wavelength and step scanning mode with step $\Delta 2\theta$ = 0.02 deg. Particular peaks of austenite and martensite were fitted in order to get intensity and angle position. The obtained data were applied in quantitative phase analysis and in residual stress evaluation.

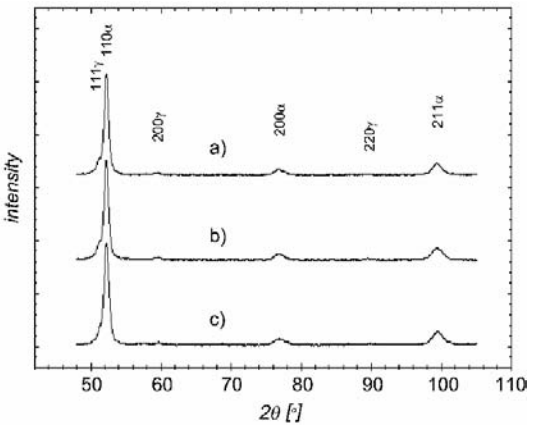

Fig. 1. Diffraction patterns of three spherical samples obtained in Bragg-Brentana geometry: a – sample INA17; b –sample INA3/1; c – sample GJ4

2.2. Methodology and measurement - X-ray diffraction quantitative phase analysis

Intensity of diffraction reflections of analyzed phase estimate volume phase fraction (Fig. 1).

For each phase (component): austenite, martensite (ferrite) with volume fraction we write individual equation for reflection intensity:

$$I^i_{hkl} = R^i_{hkl} \cdot V_i \tag{5}$$

where: i – number of phase and R^i_{hkl} – diffraction constant

Condition $\Sigma V_i = 1$ allow to solve arrangement of i-equations and to compute volume fraction any phase in mixture. In case of steels, where possibility to estimate the amount of third phase i.e. carbides (V_w) with another method e.g. quantitative metallography we can use following condition $\Sigma V_i + V_w = 1$.

Quantity of austenite (V_γ) is calculated for couple diffraction line (111) austenite and (110) martensite (ferrite) according to equation [8]:

$$V_\gamma = \frac{C \cdot \frac{I_\gamma}{I_\alpha}}{1 + C \cdot \frac{I_\gamma}{I_\alpha}} \cdot (1 - V_w) \tag{6}$$

This equation was modified for five diffraction lines: (111), (200) austenite and (110), (200) and (211) martensite:

$$V_\gamma = \frac{1 - V_w}{1 + \frac{\sum I^k_{hkl,\alpha}}{\sum I^i_{hkl,\gamma}} \cdot \frac{\sum R^i_{hkl,\gamma}}{\sum R^k_{hkl,\alpha}}} \tag{7}$$

where: Vγ -quantity of austenite; Iγ, Iα – intensity of diffraction line (γ – for austente, α - for martensite); R_α, R_γ, C - diffraction constant dependent for steel composition and measurments conditions ($C=R_\alpha/R_\gamma=1.3$); V_w - carbides content in bearing steel (in research case V_w = 6.5 %); k, i – x-ray diffraction line analysed phase α and γ.

Table 1.
Quantitative phase analysis of retained austenite (V_γ) on inner side of rings

Name of sample	Mount retained austenite according to equation for five diffraction line		
	Vγ [vol.%]	±ΔVγ/ Vγ [%]	Kind of surface treatment
INA17	11.70	0.75	smoothing
INA3/1	11.8	1.1	smoothing
INA3/2	11.6	0.6	smoothing
GI1	7.2	0.4	burnishing
GI2	7.7	0.35	burnishing
GI3	7.5	0.8	burnishing
GI4	6.0	0.3	burnishing
GI5	7.8	0.7	burnishing
GI62sz/1	15.9	0.4	grinding
GI62sz/2	16.2	0.5	grinding
GI62w/1	11.9	0.5	smoothing
GI62w/2	11.5	0.6	smoothing

2.3. Methodology and measurement - X-ray diffraction quantitative phase analysis

Applied approach to residual stress measurement was used by means X-ray diffraction $sin^2\psi$ method [11-15]. The needed diffraction patterns for residual stresses analysis were recorded by means of BRUKER D8 Advance diffractometer. The diffracted CoKα radiation was detected with a scintillation counter. The step scan of Δ2θ = 0.06º and step scanning exposition time was 5 s. Lattice deformation was measured in the spherical cap of bearings rings on crystallographic plains {111}, {110}, {200}, and {211} and ψ angle was calculated according to the equation: ψ=θ-α. A spherical area was irradiated using slit 0.1 mm.

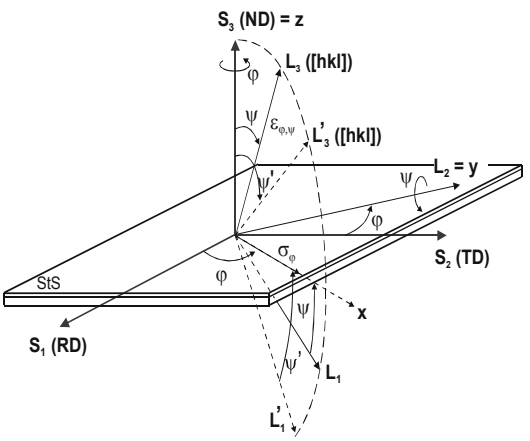

Fig. 2. Geometry of *$sin^2\psi$ method.* The $<d(\psi,\phi)>_{(hkl)}$ spacings are measured along L_3 axis in L system and the stresses σ^I_{ij} are defined with respect to the S – sample system. The horizontal angle φ is fixed during measurement. The orientation of scattering vector is characterised by the φ and ψ angles

A general description of stress measurments by X-ray diffraction methods is based on literature and on own elaborations. The average lattice strain in L_3 direction is equal to (Fig.2) [3,6,7];

$$<\varepsilon'(\varphi,\psi)>_{(hkl)} = s_1(hkl)(\sigma^I_{11}+\sigma^I_{22}+\sigma^I_{33})$$
$$+\frac{1}{2}s_2(hkl)(\sigma^I_{11}\cos^2\varphi+\sigma^I_{22}\sin^2\varphi+\sigma^I_{12}\sin 2\varphi)\sin^2\psi$$
$$+\frac{1}{2}s_2(hkl)\sigma^I_{33}\cos^2\psi+\frac{1}{2}s_2(hkl)(\sigma^I_{13}\cos\varphi+\sigma^I_{23}\sin\varphi)\sin 2\psi$$

where: $s_1(hkl)$ and $s_2(hkl)$ are diffraction elastic constants for quasi-isotropic polycrystalline and σ^I_{ij} macrostresses are defined with respect to the *S* system (Fig.2.)[7,13].

If space components of stress tensor are neglected the simplification of above equation for plain stress field (assumed for surface) can be expressed:

$$\varepsilon_{\phi},\psi = 1/2\, S_2\sigma_\varphi \sin^2\psi + S_1(\sigma_1+\sigma_2) = \frac{d_\psi - d_o}{d_o} \qquad (9)$$

$$\sigma_\varphi = \sigma_2 \sin^2\varphi + \sigma_1\cos^2\varphi \qquad (10)$$

where: σ_φ is measured stress which is composed by σ_1 and σ_2 as principal stresses of plain state of stress according to eq. 9.

Surface layers of different thickness can be measured by matching wavelength and incidence angle of X-ray beam. When Bragg-Brentano geometry or $sin^2\psi$ method is used the effective depth of penetration varies along diffraction angle θ and inclination angle ψ (Fig. 3)[3,6,7,9]

Table 2.
Macroscopic residual stress (σ_I) measurements and calculated in bearings rings

Name of sample	Component of stress	Stresses from $\sin^2\psi$ method σ_x [MPa] +-$\Delta\sigma_x$	Calculated stresses σ_x [MPa]
JNA3_2	σ_y	-713 +-38	
	σ_x	-696 +-38	-161
JNA3_1	σ_y	-652 +-32	
	σ_x	-	-150
GJ1	σ_y	-361+-21	
	σ_x	-	-316
GJ2	σ_y	-351 +-21	
	σ_x	-	-289
GJ3	σ_y	-300 +-19	
	σ_x	-	-305
GJ4	σ_y	-365 +-22	
	σ_x	-147 +-24	-356
GJ5	σ_y	-530 +-30	
	σ_x	-160 +-28	-293
GJ62sz	σ_y	-127 +-14	
	σ_x	74	
GJ62w	σ_y	-449 +-27	
	σ_x	-557 +-49	
JNA17	σ_y	-687 +-33	
	σ_x	-589 +-42	-155

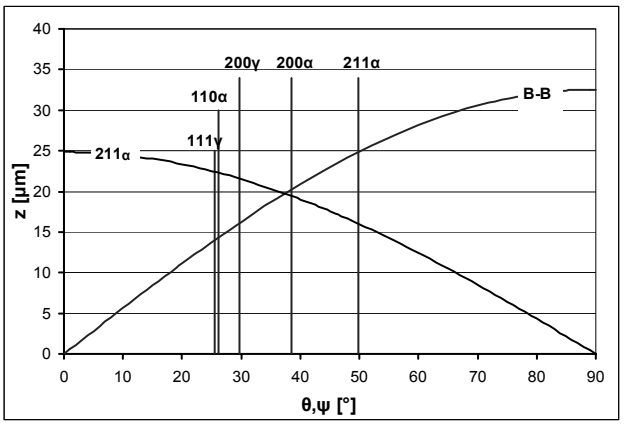

Fig. 3. Effective penetration depth (z) for Bragg-Brentano (B-B) geometry and for $\sin^2\psi$ method for {211} diffraction line

3. Discussion

This 100Cr6 bearing steel was applied in production of bearing elements like rings. This rings were prepared with different methods in goal of specific surface and surface layer properties. This different production methods result in different properties of surface layer e.g. retained austenite volume fraction and residual stresses. Results of theoretical calculations are presented in Table 2 and results of measurements are presented in Table 1 and 2.

The quantitative diffraction phase analysis of bearing balls was obtained with equation (6, 7, Tab. 1). Maximal amount was found as about 16 vol.% for GJ62sz sample, for GJ62w sample amount of austenite is about 12 vol.% and minimal content about 6 vol.% for sample GI4.

As it was mentioned in introduction the calculated stresses differ from that of measured (Tab. 2). Lowest state of compression residual stresses were found in sample GJ62sz which was surface grinding -127 MPa with tensile stress as transverse component. Much higher stress level appeared in smoothing sample about 450-550 MPa. Highest stresses (-713 MPa) were found in sample JNA3_2.

Sources of measured residual stresses in this case are following phase transition during mechanical treatment and plastic micro-deformation due to machining and directivity of mechanical treatment. That form state of stress overlap with the stresses existing after heat treatment. In order to precise interpretation of differences between following results needs another investigations: i.e. measurement of retained austenite and residual stresses in rings after heat treatment before any mechanical treatment.

4. Conclusions

1. The applied surface mechanical treatments produced different surface layers in bearing rings in terms of surface roughness and mechanical properties.
2. Elasto-plastic strains due to applied surface mechanical treatments induced phase transformation of retained austenite.
3. Volume change in surface layers accompanied to phase transformation of retained austenite. Therefore macroscopic compressive residual stresses were created.
4. The differences between calculated and measured residual stresses are caused by their gradient-like distribution versus depth under surface.

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