APPLICATION OF X-RAY DIFFRACTION AND BARKHAUSEN NOISE ANALYSIS FOR STABILITY CONTROL DURING MACHINING

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Resume
The contribution is focused on the recent experience of X-ray Diffraction Laboratory of the Czech Technical University in Prague and Department of Machining and Assembly of the Technical University of Liberec with industrial applications of X-ray diffraction residual stress measurement and Barkhausen noise analysis. Both methods are used for control and optimization of technological parameters during final surface machining of camshafts. They verify whether the required level of residual stresses in given subsurface areas was achieved and serve also as a fast output inspection of machine parts´ surface quality.

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1. Introduction

In order to minimize the costs of production, the companies working in this field require a material with specified mechanical characteristics, because engineering products' quality must unceasingly be improved. Recently, the development of analytical methods and more sophisticated technologies has enabled improvement of surface layer characteristic compared with the basic material of dynamically loaded components. The residual stresses have a significant influence on the fatigue limit; in the case of compressive surface stresses the effect is favourable, however the tensile residual stresses are detrimental and could lower the stress corrosion resistance and/or corrosion fatigue of materials [1-4].

Thus a prime target for industry is to control these residual stresses. They have to be determined and monitored during the fabrication of products to optimize the process with a view to the material properties determining its behaviour both in production and service. Therefore, criteria have to be set for the level of residual stresses with the aim to guarantee the materials shape stability and satisfactory fatigue resistance in the manufacturing process. Mechanical processes, as e.g., grinding, could induce tensile residual stresses in materials. However, they are very harmful for machine parts and can be eliminated by rolling, which increases the fatigue resistance of parts by delaying crack initiation. Also the Barkhausen noise analysis (BNA) allows a simple, fast, real time, and non-destructive testing of the level of residual stresses (RS) in ground and rolled parts of camshafts, and checking the homogeneity of the treatment. Nevertheless, this output inspection needs to be verified and confirmed by residual stress X-ray diffraction (XRD) measurements [5, 6].

2. Samples under Investigation

The effect of grinding and rolling on residual stresses and parameters of BNA was studied on material 16MnCrS5+HH (42 - 47 HRC) in a machined surface layer of three camshafts (*A, B, C*) of Diesel injection pump Common Rail. XRD and BNA on surfaces were performed in axial and tangential directions on two selected parts, lobe 1 and lobe 2 namely on flat surfaces (*b, d, f*) and curved surface areas (*a, c, e*). Depth distributions of residual stresses and the magnetoelastic parameter in the case of sample *A* only were determined on two selected parts on the flat surface (d_1) and curved surface area (a_1). The measured areas are depicted schematically in Fig. 1.

3. Experimental

3.1 X-ray diffraction technique

XRD "one-tilt" method was applied to study the biaxial state of RS [7]. The incident X-ray CrKα beam directed by a cylindrical collimator 1.7 mm in diameter reached the sample surface at an angle of ψ_0 = 45° in the axial and radial directions, in which the surface components of stress σ_A and σ_T, respectively, were analyzed. The record of the {*211*} α-Fe diffraction line profiles was obtained from a position sensitive detector (imaging plate). The experimental inaccuracy did not exceed 40 MPa.

3.2 Barkhausen noise analysis

The magnetoelastic parameter mp was chosen as a characteristic of surface and subsurface layers. This parameter corresponds to the integral intensity of Barkhausen noise, i.e. discontinuous magnetisation. Further parameters, for example coercivity and remanence from hysteresis loop, were analysed as well. The measurements were performed using a commercial unit *Stresstech MicroScan 600-1* magnetoelastic analyser with a standard sensor S1-138-15-0. The main parameters of the applied method were: sinusoidal shape of magnetic signal, magnetic voltage 9V, and frequency 220 Hz with band filter 70-200 kHz. The results obtained are mean values from 10 measurements. The penetration depth of the excitation signal depends on the used frequency and the analysed material [8]. In practice, the typical expectable penetration depth in this experimental arrangement is in the range of 10 μm.

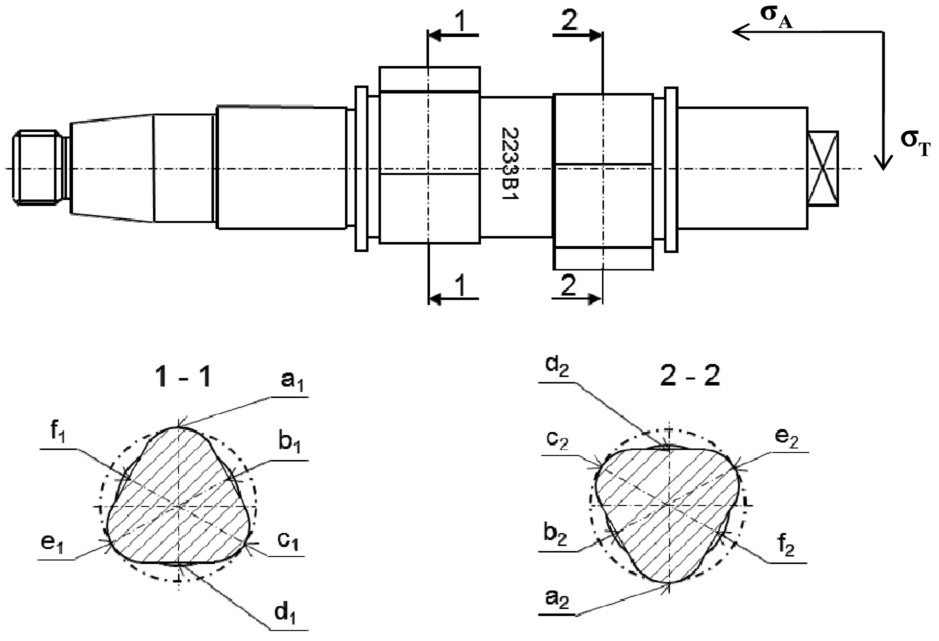

Fig. 1. Schematic of the measured areas on the sample with marked directions of stress determination σ_A, σ_R

3.3 Determination of residual stress and magnetoelastic parameter depth profiles

Due to the penetrating limitations of X-rays and Barkhausen noise, both the methods can be used non-destructively only for surface layers of few micrometres in thickness. In the case of conventional XRD equipment and magnetoelastic method of BNA, investigation of stress depth profiles and profiles of magnetoelastic parameter are performed in combination with electrochemical polishing. The process of anodic dissolution takes place during electrochemical etching. While the anode is formed by the sample itself, the product of this process is a solution of high electrical resistance which is embedded into microscopic wells in the surface of the sample and, therefore, preferential removal of roughness proceeds [9].

3. Results and their discussion

The XRD representative results of macroscopic residual stresses for sample *A* from the lobe 1 ($a_1 - f_1$) and 2 ($a_2 - f_2$) obtained from the surface, are shown in Fig. 2. The selected values of magnetoelastic parameter (*mp*), remanence (B_r), coercivity (H_c) and with of burst (*FHVM*) from BNA, for sample *A*, are illustrated in Figs. 3 – 7.

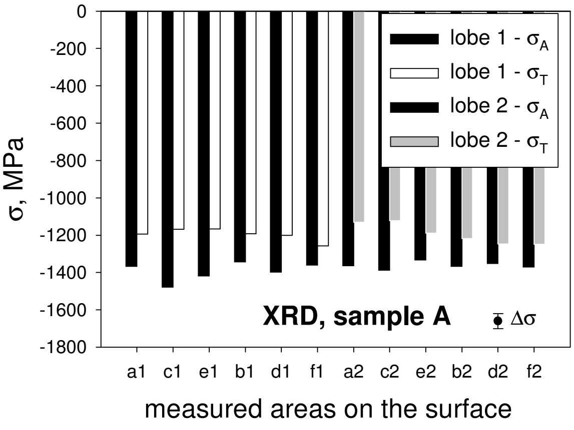

Fig. 2. Surface macroscopic residual stresses in axial (σ_A) and tangential (σ_T) directions obtained from the lobe 1 and 2 of the sample A (see Fig. 1)

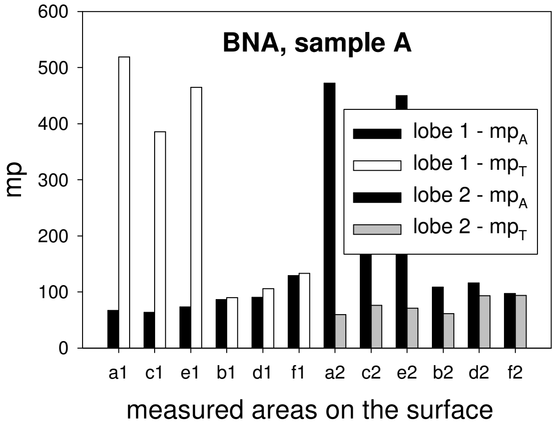

Fig. 3. Magnetoelastic parameter in axial (mp_A) and tangential (mp_T) directions obtained from the surface of the lobe 1 and 2 of the sample A

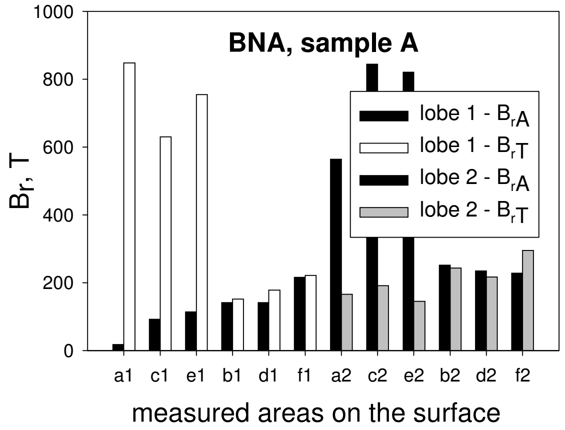

Fig. 4. Remanence in axial (B_{rA}) and tangential (B_{rT}) directions obtained from the surface of the lobe 1 and 2 of the sample A

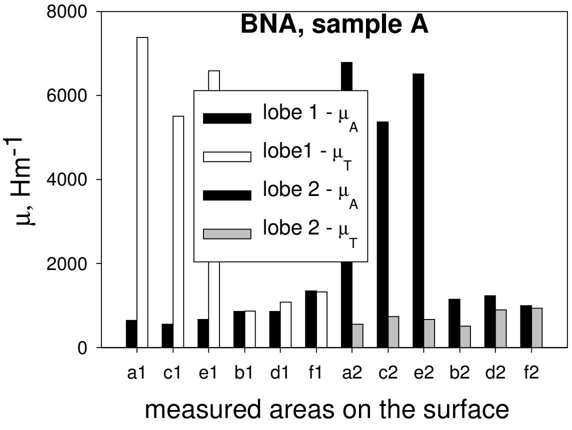

Fig. 5. Permeability in axial (μ_A) and tangential (μ_T) directions obtained from the surface of the lobe 1 and 2 of the sample A

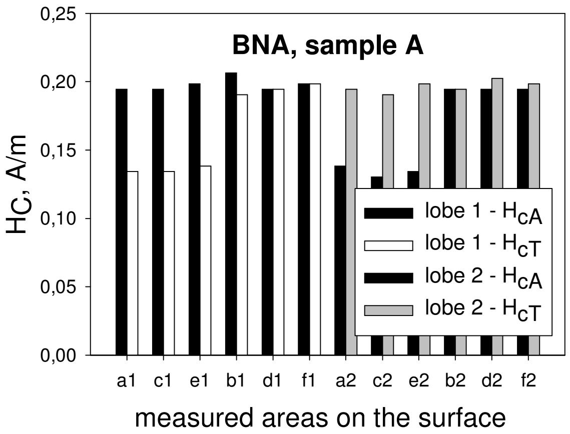

Fig. 6. Coercivity in axial (H_{cA}) and radial (H_{cR}) directions obtained from the surface of the lobe 1 and 2 of the sample A.

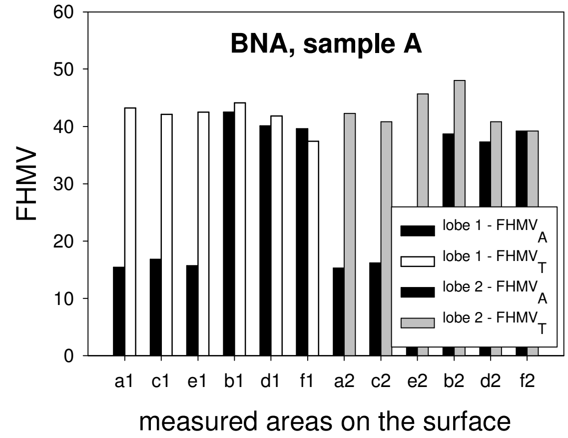

Figure 7. Width of BN burst in axial ($FHMV_A$) and tangential ($FHMV_T$) directions obtained from the surface of the lobe 1 and 2 of the sample A.

- In all investigated surface areas of camshafts *A, B, C,* beneficial compressive residual stresses higher than required -900 ± 50 MPa were observed.
- The observed differences in residual stress values between separately analysed areas, lobe 1 ($a_1 - f_1$) and lobe 2 ($a_2 - f_2$) of the camshafts *A, B, C* are probably caused by basic material inhomogeneity and instability of machining process.
- Significantly higher value of *mp* in tangential direction on curved surfaces ($a_{1,2}$, $c_{1,2}$ and $e_{1,2}$) than the values *mp* on flat surfaces ($b_{1,2}$, $d_{1,2}$ and $f_{1,2}$) are caused by deeper structural or experimental conditions required more studies later.
- In all the studied cases the mp_A values are smaller than mp_T . This effect is caused by mechanical interaction of the cutting tool, i.e. grinding wheel, with the surface of the analysed camshaft. Absolute values of RS σ_A and σ_T exihibit the same relation. This finding is in accordance with the theoretical knowledge stating that compressive RS should reduce *mp* value.
- Magnetic methods are sensitive to both stress and the microstructure characteristics [10]. Remanence is very sensitive to the real structure, while coercivity is determined only by the state of residual stresses. The magnetoelastic parameter is a function of hardness and of residual stress state (se Figs. 3 – 7). Exact analysis of the above mentioned parameters is in progress. Fig. 7 shows the dependence of BN burst widh (FHMV) in different places of lobes from camshaft *A*.

The chosen results of macroscopic residual stresses gradients (XRD) and magnetoelastic parameter, remanece, permeability, coercivity and full width half maximum of the envelope curve of the rectified BN burst from area d_1 obtained for sample *A* using gradual polishing of the surface are illustrated in Figs. 8 - 13.

- Beneficial depth distributions of compressive residual stresses were observed in both the investigated areas a_1 and d_1 of the sample *A* by XRD analysis, which from the surface to a depth of 0.030 mm have a higher absolute value in axial direction (σ_A) than in radial direction (σ_T).
- The values of residual stresses in depth 0.03 mm and 0.06 mm under surface determined by XRD in both directions accord with the demands that compressive RS in the depth of 0.03 mm should be greater than –1330 ± 120 MPa and in 0.06 mm greater than –1050 ± 70 MPa.

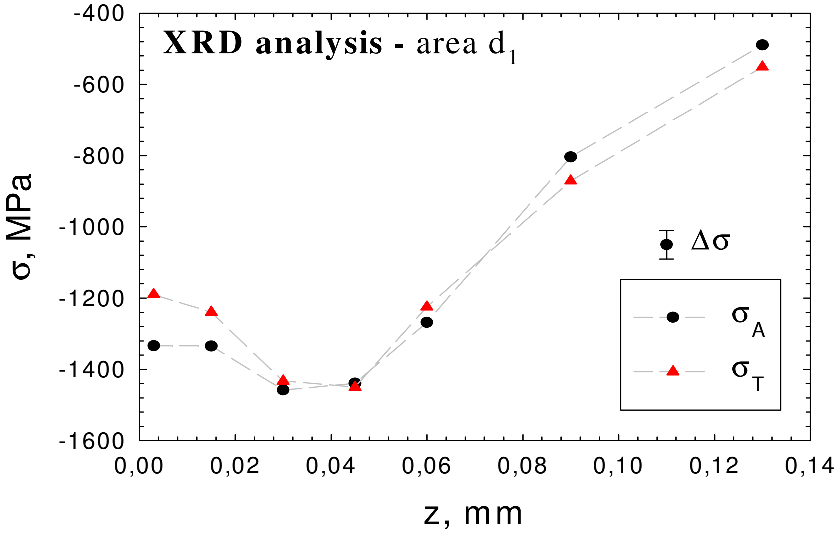

Fig. 8. Gradient of macroscopic residual stresses (σ_A, σ_T) determined by XRD from area d_1 (sample A)

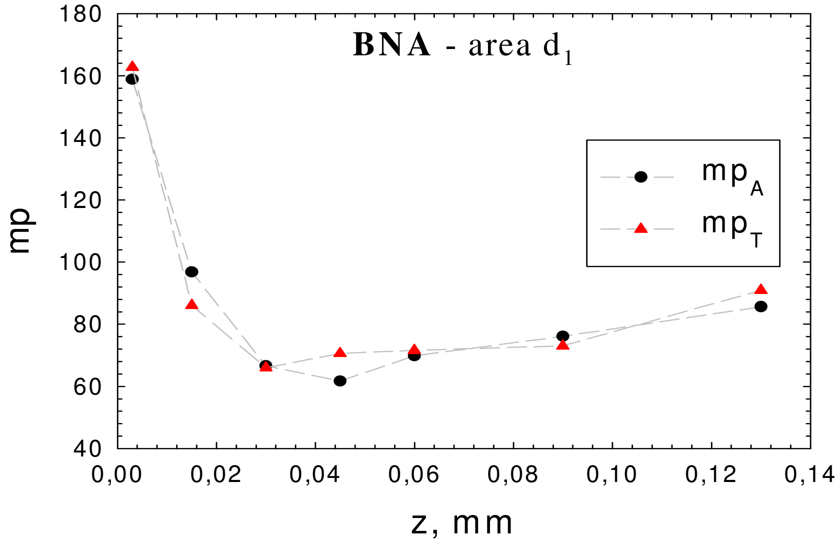

Fig. 9. Gradients of magnetoelastic parameter (mp_A, mp_T) determined by BNA from area d_1 (sample A)

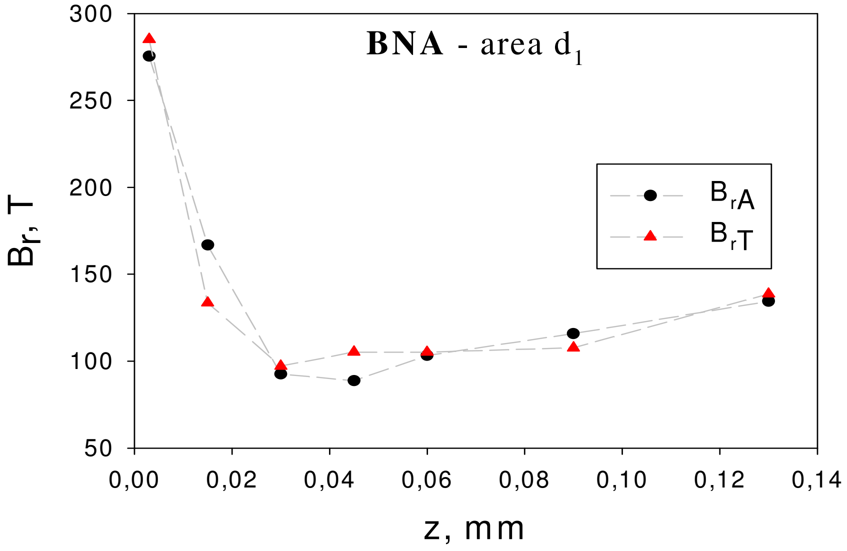

Fig. 10. Gradient of remanence (B_{rA}, B_{rT}) determined by BNA from area d_1 (sample A)

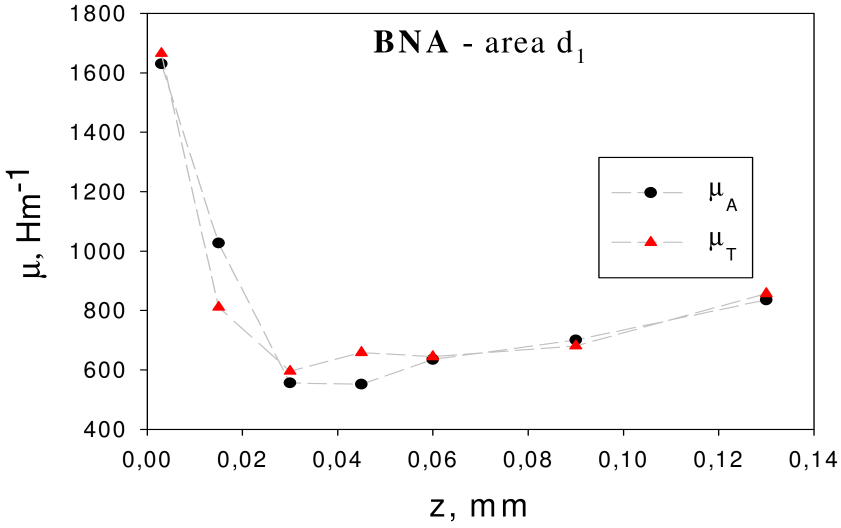

Fig. 11. Gradient of permeability (μ_A, μ_T) determined by BNA from area d_1 (sample A)

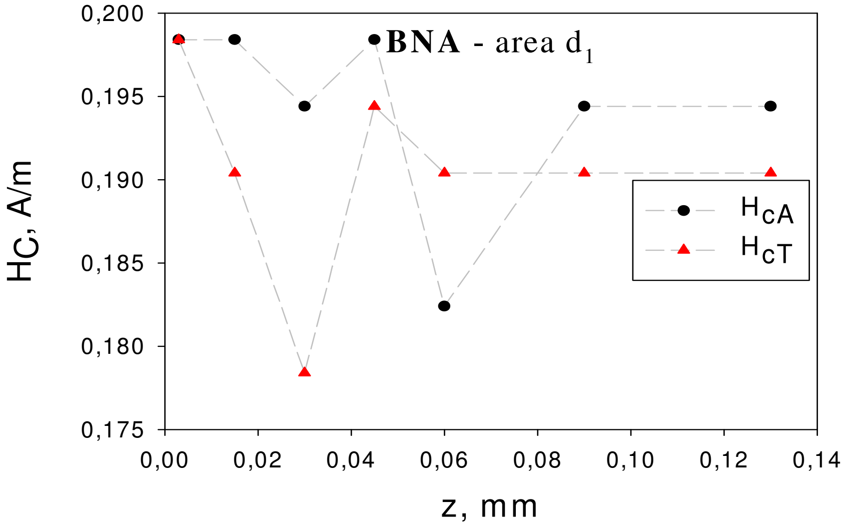

Fig. 12. Gradient of coercivity (Hc_A, Hc_T) determined by BNA from area d_1 (sample A)

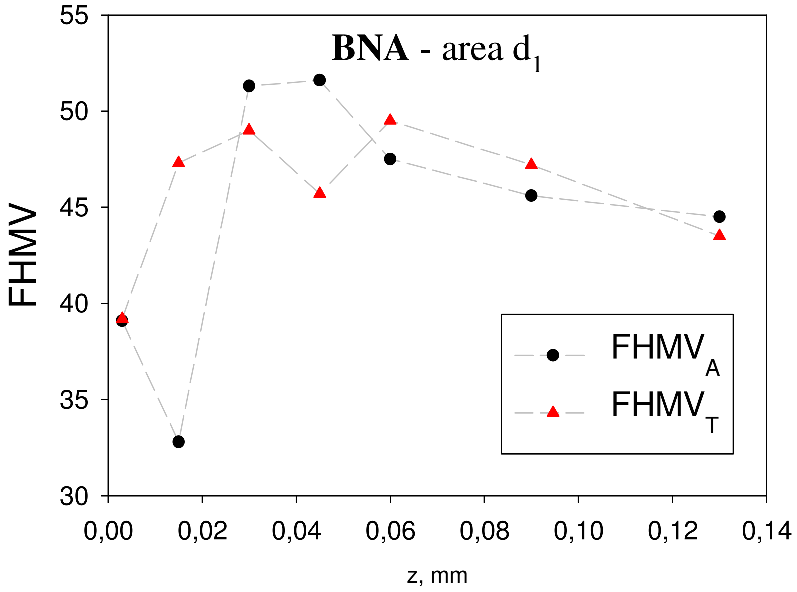

Fig. 13. Gradient of width FHMV ($FHMV_A$, $FHMV_T$) determined by BNA from area d_1 (sample A)

- Both RS depth distributions determined by XRD are qualitatively and quantitatively similar. Their shape corresponds to our expectations and is in compliance with the observed RS depth distributions in metals after finishing technologies, i.e. roller burnishing and ensuing circumferential grinding.
- Depth distributions of *mp* determined by BNA are qualitatively and quantitatively similar (excepting radial direction in area a_1 caused by due to the effect of problematic experimental conditions or some structural parameters)
- In the case of mp_A and mp_T gradients from subsurface direction relation is not observed.

4. Conclusions

Comparing residual stress and magnetoleastic parameter depth distributions observed by XRD and BNA respectively, it can be established that whilst the values of *mp* descend from surface to a depth of 0.03 mm and further change in deeper areas is not visible, compressive RS reach their maximum at a depth of 0.03 mm and steadily grow and, in a depth of 0.130 mm have only 30% of the extreme level. Low anisotropy of RS to a depth of 0.03 mm was also observed in both the investigated areas, where the level of compressions was higher in the axial direction. This effect is caused by the feed of the cutting tool in radial direction, when a lengthening of the subsurface layers resulted from mechanical interaction of the cutting edge tool with material.

XRD stress determination and BNA are rapidly growing techniques gaining attention not only in academic institutes, but also in industry. All over the world, several government and private laboratories have been founded, offering their service and consultancy to a wide and diverse group of customers. Hence, another goal of our investigation was to offer a brief review of XRD and BNA comparison which would be of special use for technologists and staff of technological laboratories and technical universities as well as designers from various industries.

It is generally acknowledged that the majority of machine components' failures are caused by the fatigue of material often initiated by cyclic loading. It has been shown that, in general, compressive RS in the material can favourably reinforce the dynamic strength by about 50 %; on the other hand, tensile RS could reduce the dynamic strength by about 30 %. Together with the phase transformations, RS form an important factor affecting the failure. Moreover, diligent analyses of such failures have furnished sufficient evidence that local properties of the most severely loaded zone, which is often the surface, are crucial.

The sensitivity of fatigue limit is most pronounced on the surface and it depends on the locally changed properties of the surface layer after a technological treatment. Such surface is also distinguished by the elevated probability of deformed grains, vacations, and dislocations, which had come to life as a result of plastic deformation and thermal fields present during manufacturing. In this respects, the XRD technique for stress analysis in combination with fast method of BNA are two optimal analytic techniques for surface structure and surface properties investigation.

To summarize all conclusions, magnetoelastic parameter (mp) such as remanence (Br) and permeability (μ) correlates with residual stress and can be used for fast industrial control.

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