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Experimental Stress Analysis

Investigation of Camshafts after Machining Using X-ray Diffraction and Barkhausen Noise Analysis

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Abstract: 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.

Keywords: X-ray diffraction, Residual stress, Barkhausen noise analysis, Surface integrity

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 of materials [1, 2].

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 [3].

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2. Samples under investigation

The effect of grinding and rolling on residual stresses and parameters of BNA was studied on material 16MnCrS5+HH 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 radial directions on two selected parts, cam 1 and cam 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.

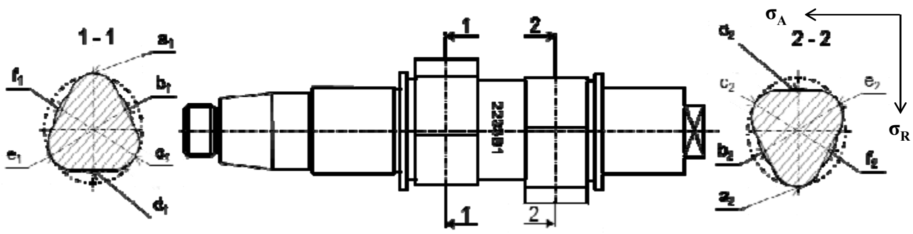

Fig. 1. Schematic of the measured areas on the sample with marked directions of stress determination σ_A, σ_R

3. Experimental

3.1 X-ray diffraction technique

XRD "one-tilt" method was applied to study the biaxial state of RS [4]. 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_R, 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. 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 [5]. In practice, the typical expectable penetration depth in this experimental arrangement is in the range of 10 μm.

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 etching. 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 [6]. The *LectroPol-5* by *Struers* – a device for automatic microprocessor controlled electrolytic polishing and etching of metallographic specimens – was used for surface layer removal.

4. Results and their discussion

The XRD results of macroscopic residual stresses from cam 1 ($a_1 - f_1$) and cam 2 ($a_2 - f_2$) obtained from the surface as well as the average value of the width of the {*211*} diffraction line, which could be interpreted as a degree of plastic deformation of the crystal lattice, are shown in Figs. 2 - 5. The selected values of magnetoelastic parameter (*mp*), remanence (B_r) and coercivity (H_c) from BNA, for sample *A*, are illustrated in Figs. 6 – 8.

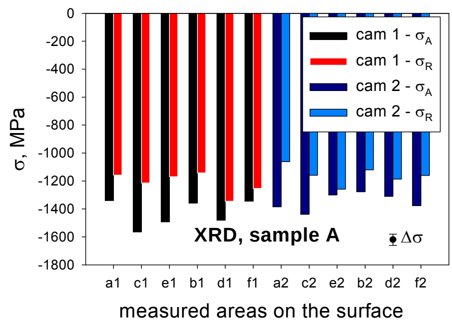

Fig. 2. Surface macroscopic residual stresses in axial (σ_A) and radial (σ_R) directions obtained from the cam 1 and 2 of the sample *A* (see Fig. 1)

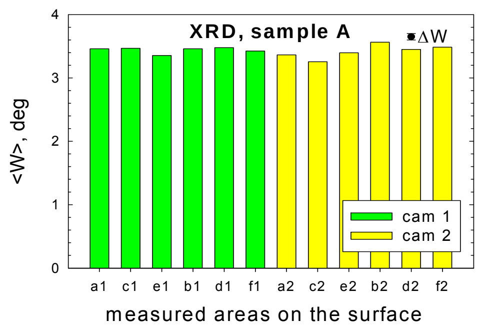

Fig. 3. Average surface values of the {*211*} α-Fe diffraction line width from axial and radial direction for the cam 1 and 2 of the sample *A*

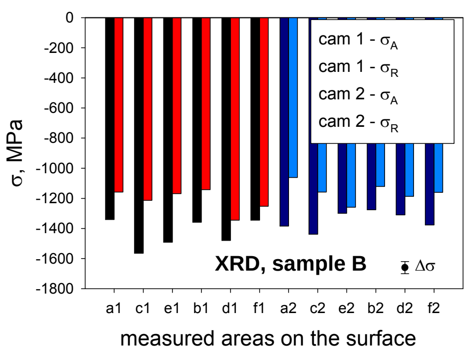

Fig. 4. Surface macroscopic residual stresses in axial (σ_A) and radial (σ_R) directions obtained from the cam 1 and 2 of the sample *B*

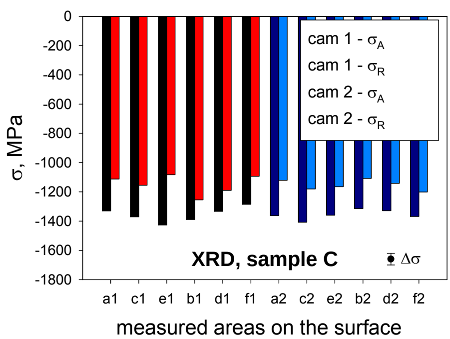

Fig. 5. Surface macroscopic residual stresses in axial (σ_A) and radial (σ_R) directions obtained from the cam 1 and 2 of the sample *C*

- In all the investigated surface areas of camshafts *A*, *B*, *C*, beneficial compressive RS (see Figs. 2, 4 and 5) higher than required – 900 ± 50 MPa were observed.

- Differences in the residual stress values between separately analysed areas, cam 1 ($a_1 - f_1$) and cam 2 ($a_2 - f_2$) of camshafts *A*, *B*, *C* are probably caused by basic material inhomogeneity and instability of the machining process.
- From the average surface values of the width of *{211} α-Fe* diffraction line, no quantitative and qualitative difference is visible between the flat and curved surfaces of camshafts *A*, *B*, *C* (as illustrated for sample *A* in Fig. 3).

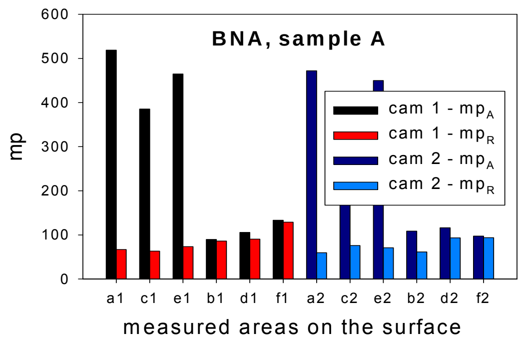

Fig. 6. Magnetoelastic parameter in axial (mp_A) and radial (mp_R) directions obtained from the surface of the cam 1 and 2 of the sample *A*

- Significantly higher values of *mp* in axial 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 imperfect contact of the standard sensor with the measured area. To eliminate this effect a special sensor with shape correction should be used.

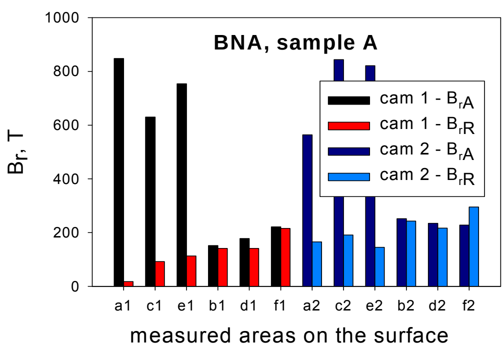

Fig. 7. Remanence in axial (B_{rA}) and radial (B_{rR}) directions obtained from the surface of the cam 1 and 2 of the sample *A*

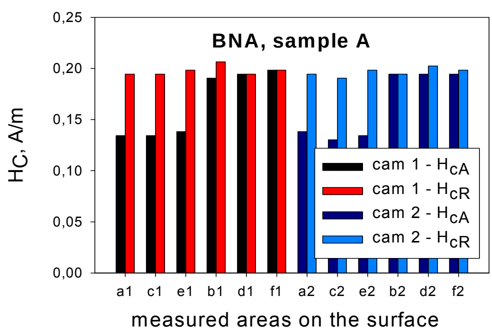

Fig. 8. Coercivity in axial (H_{cA}) and radial (H_{cR}) directions obtained from the surface of the cam 1 and 2 of the sample *A*

- In all the studied cases the mp_A values are larger than mp_R (Fig. 6). This effect is due to mechanical interaction of the cutting tool, i.e., the grinding wheel, with the surface of the analysed camshaft. The absolute values of RS σ_A and σ_R exhibit the same relation. This finding is contrary to the theoretical knowledge valid for magnetoelastic parameter *mp* stating that compressive residual stresses should reduce *mp* value. On the other hand, it was observed that for the ground and rolled hardened steel a higher *mp* parameter is obtained, probably due to changes of subgrain (dislocation) structure.

- Magnetic methods are sensitive to both stress and the microstructure characteristics [7]. 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 (see Figs. 6 – 8). Exact analysis of the above mentioned parameters is in progress.

The results of gradient of RS (XRD) and *mp* (BNA) from areas a_1 and d_1 obtained for sample *A* using gradual etching of the surface are illustrated in Figs. 9 - 13.

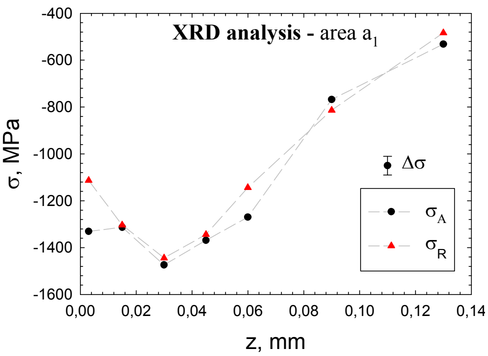

Fig. 9. Gradient of macroscopic residual stresses (σ_A, σ_R) determined by XRD from area a_1 (sample *A*)

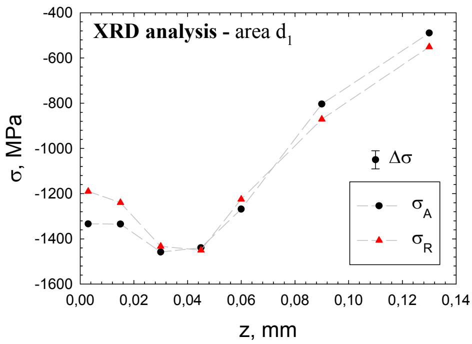

Fig. 10. Gradient of macroscopic residual stresses (σ_A, σ_R) determined by XRD from area d_1 (sample *A*)

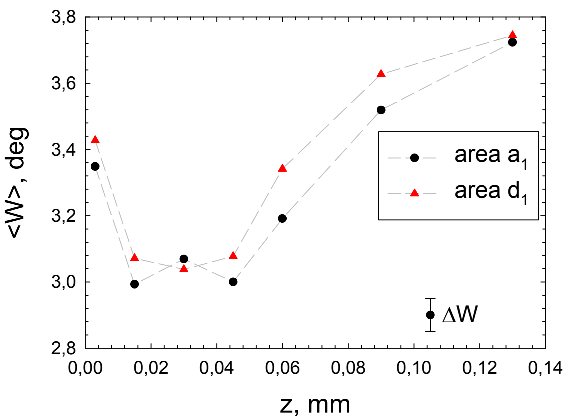

Fig. 11. Average width of the *{211} α-Fe* diffraction line obtained from areas a_1 and d_1, determined by XRD (sample *A*)

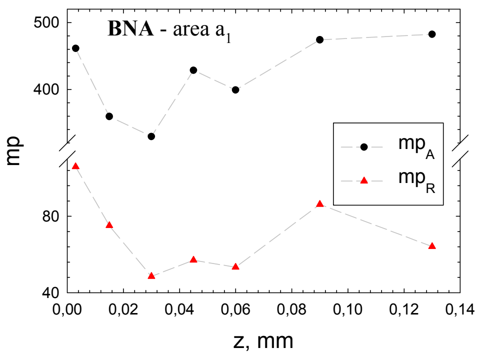

Fig. 12. Gradient of magnetoelastic parameter (mp_A, mp_R) determined by BNA from area a_1 (sample *A*)

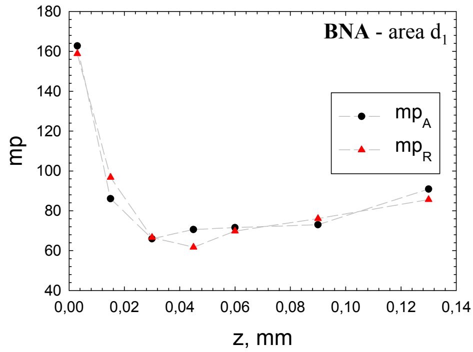

Fig. 13. Gradient of magnetoelastic parameter (mp_A, mp_R) determined by BNA from area d_1 (sample *A*)

- 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 (see Figs. 9 and 10), 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_R).
- 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.
- Both RS depth distributions determined by XRD (Figs. 9 and 10) 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.
- Combination of grinding and rolling treatment leads to hook-like depth distributions of diffraction line width. In the cutting place the grinding process generates very high temperature resulting in a lower value of diffraction line width compared to that of the basic material. This effect is caused by thermal relaxation of microstresses, i.e. stresses of type II. Since the diffraction line width after rolling is higher in the near-surface region than in depth, the plastic deformation caused by this treatment is more significant as against thermal loading due to grinding. Differences in depth distribution of areas a_1 and d_1 are not perceptible.
- Depth distributions of *mp* determined by BNA (Figs. 12 and 13) are qualitatively and quantitatively similar (excepting axial direction in area a_1 due to the effect of insufficient contact with standard sensor).
- In the case of mp_A and mp_R subsurface gradients no directional relation is observed.

5. 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 was 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.

Acknowledgements

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