ANALYSIS OF RESIDUAL STRESS STATE IN SPEED GEARS FOR AUTOMOTIVE VEHICLES

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ABSTRACT

Residual stress profiles in speed gears for automotive vehicles were determined. The profiles were measured at the root between two teeth of the gears by x-ray diffraction. The gears were cemented, quenched and annealed. After these heat treatments, compressive residual stresses were introduced by shot-peening. The profiles of stress distribution indicate the maximum of compressive residual stress (-950 MPa) at a depth of 0.05 mm. The stresses decrease to zero at a depth of 0.25 mm. In the gears without shot-peening the maximum of compressive residual stress (-600 MPa) is on the surface and decrease to zero at a depth of 0.30 mm.

INTRODUCTION

In order to improve the fatigue and corrosion resistance of steels and steel parts, compressive residual stresses are usually introduced on the surface of these parts.

The automotive industry utilizes this method in various types of pieces like springs and speed gears. It is known that the stress distribution along the depth of the surface depends on the material mechanical properties and on the geometry of the treated part [1,2]. This means that it is very difficult to predict the parameters of stress distribution for curvilinear surfaces like the root of speed gears.

In this work the residual stress distribution at the root of automotive speed gears was studied by x-ray diffraction. The stress state was analyzed for gears after machining plus heat treatment and after additional shot-peening treatment.

MATERIALS AND METHODS

The initial stress state of gears is created by all previous technical operations: machining and heat treatment, including cementation, quenching and annealing. The subsequent shot-peening introduces additional compressive stresses thus creating quite a complex final stress distribution.

In this paper two types of samples of machined and heat treated gears, one with and another without shot-peening, were studied. Figure 1 illustrates a scheme of the analyzed gear and shows the points and directions of stress measurements. Two points located on opposite sides were measured.

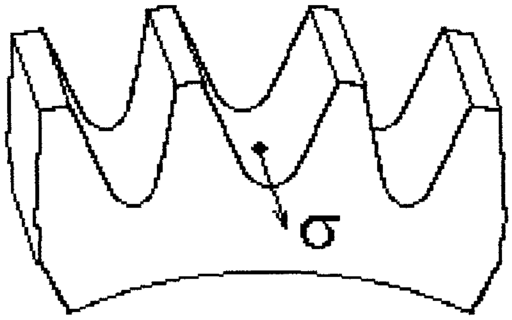

Figure 1. Points and directions of the measurements.

Stress measurements were made with the same portable x-ray apparatus presented at the 48th Denver Conference [3], except for the use of a new collimator – cassette unit that allows to record the reflections passing between two teeth of the gear and carry out the measurement of longitudinal stress component without any cutting of the gear. The portable apparatus consists on the following units (see fig.2):

1. Power and control unit which supplies a high voltage source and allows to control the X-ray tube anode current and voltage. The weight and size of the unit are 1.5 kg and (20x12x8) cm^3, respectively.
2. A high voltage source and X-ray tube. The distinctive design of this unit lies on the fact that the X-ray tube is coupled to a high voltage source. The cylindrical part of the source body is 5 cm in diameter and 37 cm long. The air cooled X-ray tube, operated at 25 kV and 2 mA, has two anodes which emit two convergent X-ray beams. The convergence angle is 50 degrees and may be selected by collimator slits from 40 to 60 degrees. The weight of the high voltage source with X-ray tube is 2.5 kg.
3. A magnetic support which allows to fix the apparatus to any ferromagnetic plate, or directly to the metal object.
4. A collimator unit with film cassette for stress measurement. Two cassette windows provide record of diffraction lines in 2θ angular intervals from 148 to 164 degrees (fig.3).

The film reading is carried out by a microdensitometer controlled by computer. Line position is determined by approximation of the profile with double Cauchy function. The coefficients of the Cauchy function are determined by regularisation method.

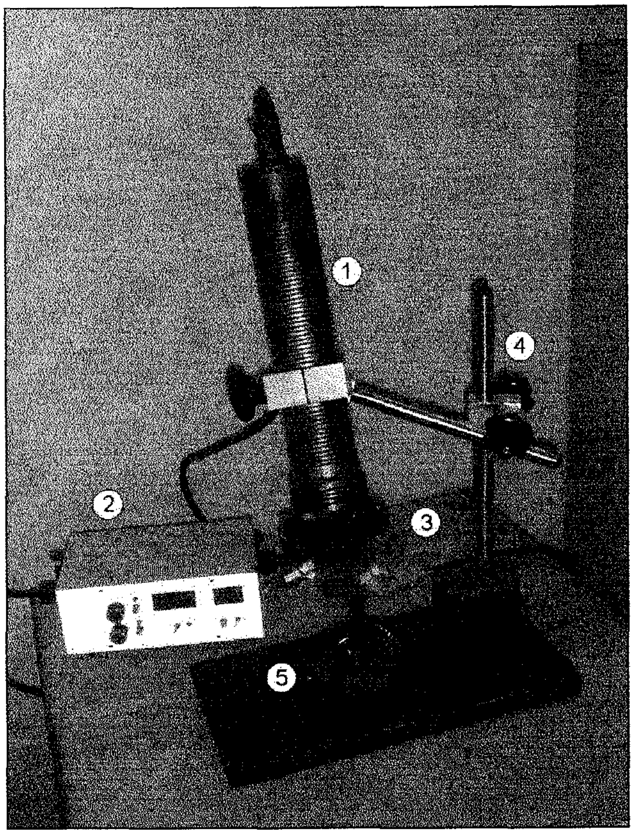

Figure 2. Portable apparatus for stress measurements1-power and control unit; 2-high voltage source; 3-collimator with film cassette; 4-magnetic support.

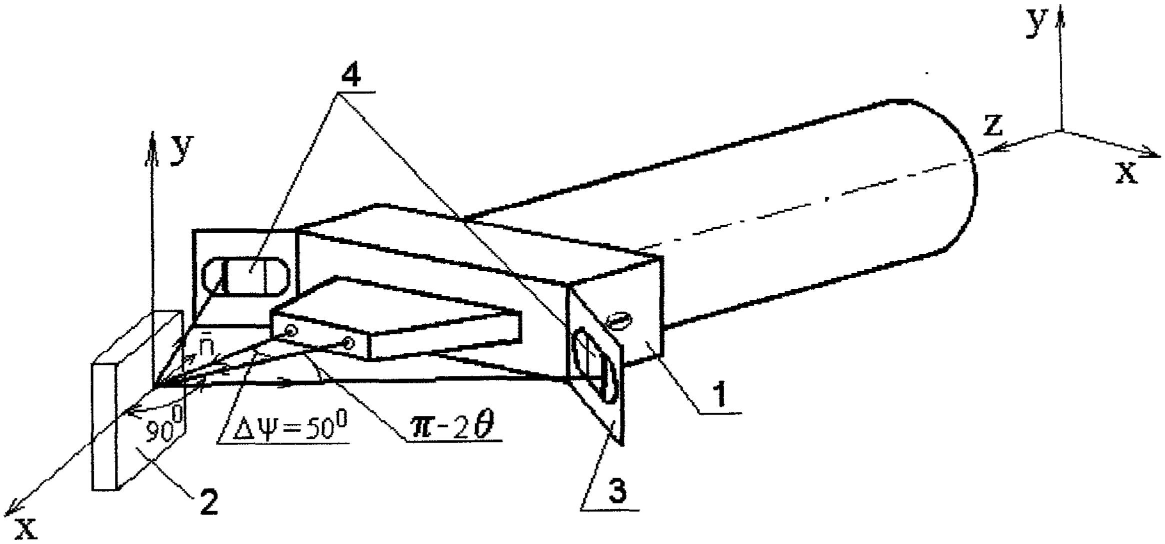

Figure 3. New collimator and measurement scheme.
1 – collimator for the two incident beams with angles $\psi = 0^0$ and $\psi = 50^0$; 2- sample; 3- film cassette; 4 – windows with the diffracted and reference lines.

Surface layers were removed by electropolishing in order to determine the stress distribution along the depth of the root.

STRESS MEASUREMENT METHODOLOGY

Double exposure technique is used with the portable apparatus. It is based on measurements of two strain components $\varepsilon_{\varphi,\psi 1}$ and $\varepsilon_{\varphi,\psi 2}$ determined by the following formula [3]:

$$\varepsilon_{\varphi,\psi} = \frac{1+\nu}{E}\sigma_\varphi \cdot sin^2\psi - \frac{\nu}{E}(\sigma_1 + \sigma_2), \qquad (1)$$

where E and ν are elastic constants of the material, ψ and φ - polar and azimuthal angles, σ_φ - a measured stress component, σ_1 and σ_2 - the principal stresses.
The difference between the two strain components is equal to

$$\varepsilon_{\varphi,\psi_2} - \varepsilon_{\varphi,\psi_1} = \frac{1+\nu}{E}\sigma_\varphi\left(sin^2\psi_2 - sin^2\psi_1\right), \qquad (2)$$

The stress component σ_φ from the expression (2) can be written as:

$$\sigma_\varphi = \frac{E}{1+\nu}\frac{\varepsilon_{\varphi,\psi_2} - \varepsilon_{\varphi,\psi_1}}{sin^2\psi_2 - sin^2\psi_1}, \qquad (3)$$

The strain expressed by the diffraction terms is:

$$\varepsilon_{\varphi,\psi} = \frac{d_{\varphi,\psi} - d_0}{d_0} = -ctg\theta_0\left(\theta_{\varphi,\psi} - \theta_0\right), \qquad (4)$$

where $d_{\psi,\varphi}$, d_0 and $\theta_{\psi,\varphi}$, θ_0 are the interplanar distances and the diffraction angles of stressed and unstressed material respectively.
From expressions (3) and (4) the final formula for determination of the stress component σ_φ may be obtained as

$$\sigma_\varphi = -\frac{E}{1+\nu}\frac{ctg\theta_0\left(\theta_{\varphi,\psi_2} - \theta_{\varphi,\psi_1}\right)}{sin^2\psi_2 - sin^2\psi_1}, \qquad (5)$$

Thus, to determine any stress component it is necessary to measure the diffraction angles corresponding to reflection from lattice planes with normals characterised by angles ψ_1 and ψ_2. Figure 4 shows stereographic projections for stress measurements made with the portable apparatus using a collimator as described in [3] and the new one shown on figure 3. According to figure 5, $\psi_1 = -12^0$ and $\psi_2 = 62^0$ for the new collimator. The angle difference $\Delta\theta = \theta_{\psi 2} - \theta_{\psi 1}$ on equation (5) can be expressed as:

$$\Delta\theta = K\left(L_{50} - L_0\right) \qquad (6)$$

where L_{50} and L_0 are the distances from the diffraction lines to a reference mark, and K is the scale and transfer coefficient from linear units to angle units.

Film reading to determine the values of L_{50} and L_0 is made by a computer controlled microdensitometer. The software for measuring the diffraction line position is based on an approximation of the line profile by a double Cauchy function. Parameters of approximating function are determined by regularisation method.

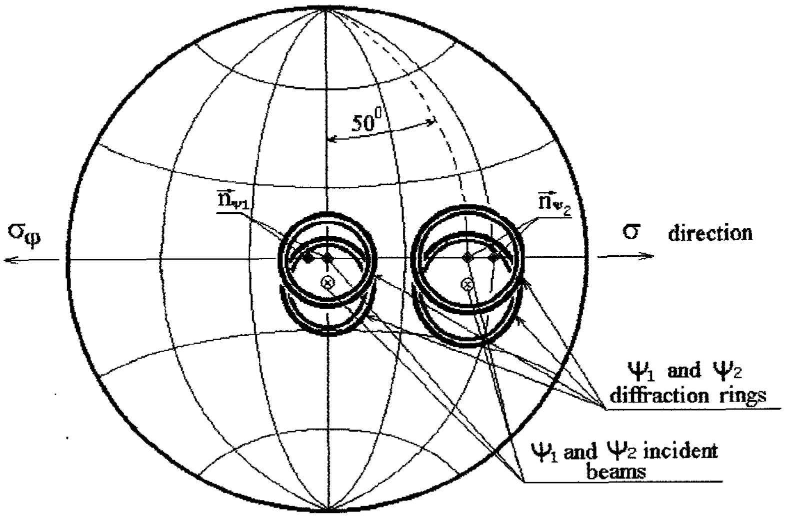

Figure 4. Stereographic projection of the ψ - goniometer geometry used in the portable X-ray apparatus.

Substitution of expression (6) into equation (5) leads to the following formula for stress calculation:

$$\sigma = A\left(L_{50} - L_0\right) \qquad (7)$$

where A is the constant including all known quantities entering into equation (5). The value of the coefficient A is a characteristic of the equipment and it is determined from a calibration exposure of any unstressed material.

RESULTS AND DISCUSSION

Profiles of stress distributions through the thickness for the gears without shot-peening are presented on figures 5 and 6, and residual stress profiles for shot-peened gears are presented on figures 7 and 8. P1 and P2 represent opposite sides of the gears.

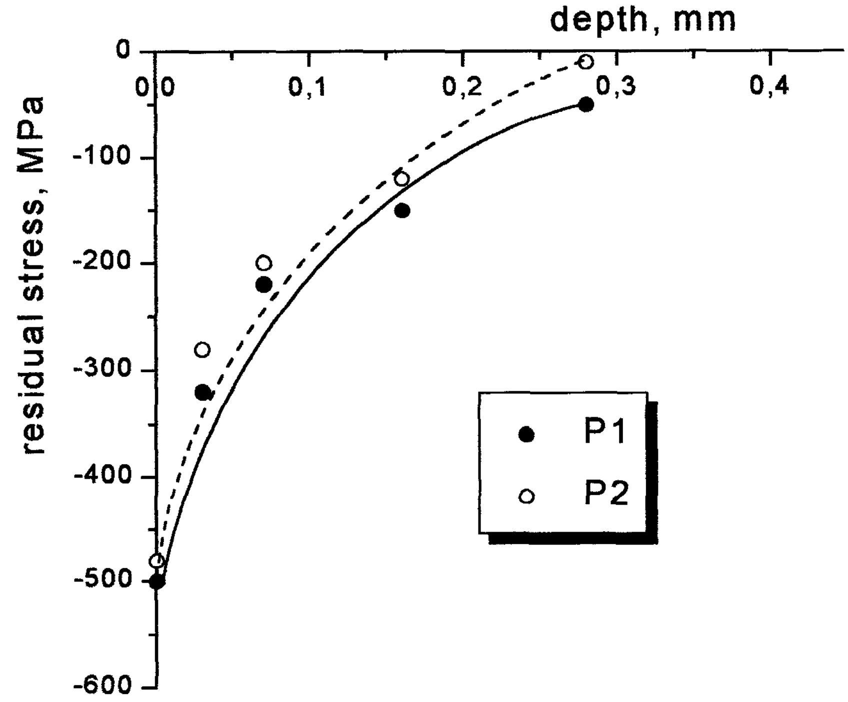

Figure 5. Residual stress profiles in the speed gear A1 without shot peening.

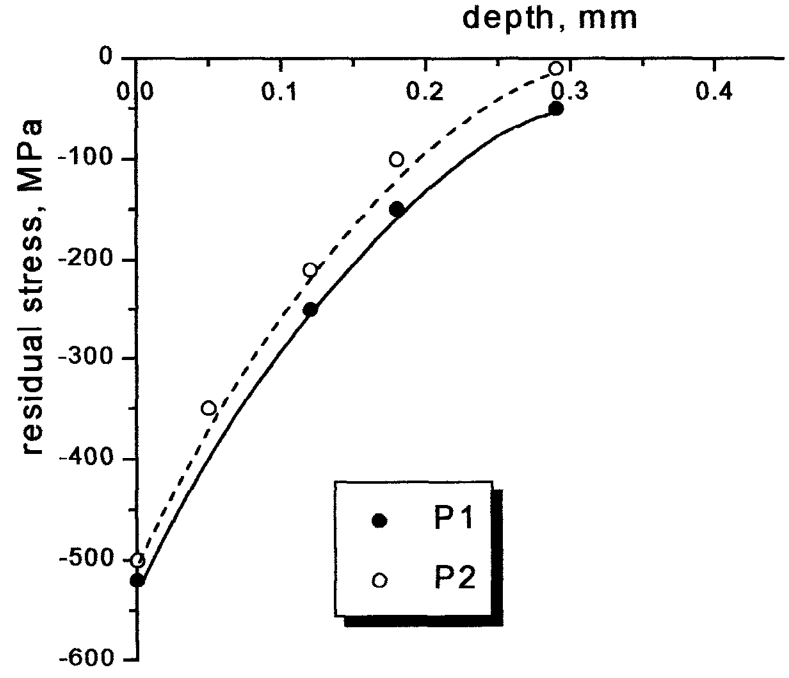

Figure 6. Residual stress profiles in the speed gear A2 without shot peening.

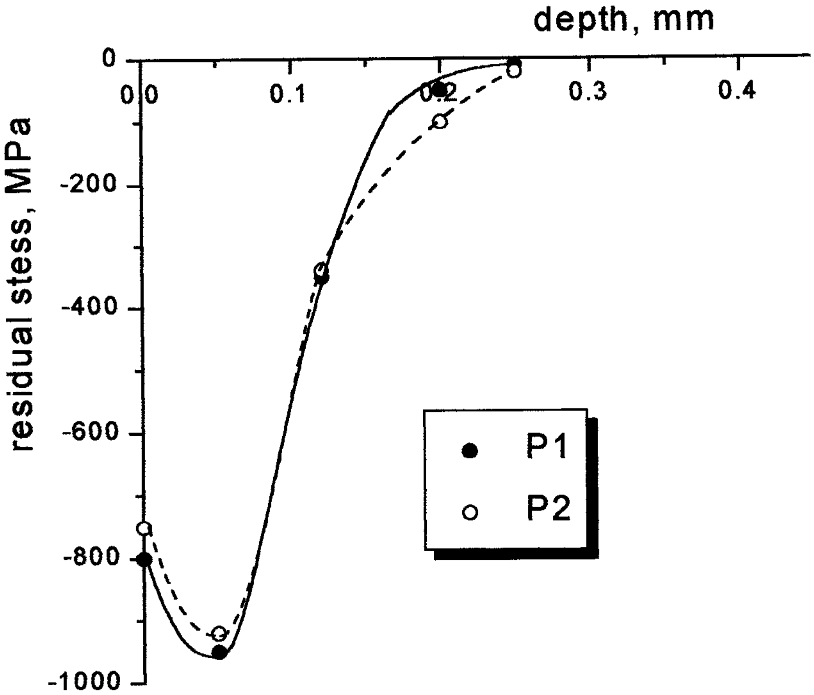

Figure 7. Residual stress profiles in the speed gear B1 after shot peening.

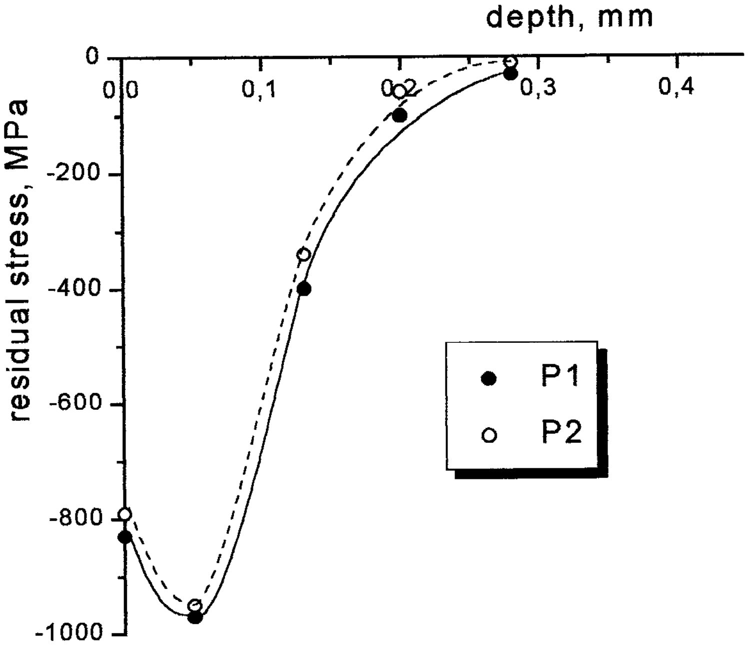

Figure 8. Residual stress profiles in the speed gear B2 after shot peening.

It can be seen that the shape of the profiles is different for these two types of analyzed gears. Stress distribution in the gears without shot-peening is typical for cemented and quenched material and it features a parabolic profile.

The profiles of stress distribution in gears after shot-peening are typical for this kind of surface treatment [1]. They are characterized by a maximum of compressive stress after removal of a surface layer. In our case the maximum of residual stress is at a depth of 0.05mm.

CONCLUSIONS

A new engineering application of stress measurements with the x-ray diffraction portable apparatus has been presented. Stress distribution along the depth of surface have been carried out for automotive speed gears after heat treatment, including cementation and quenching, and for gears after shot-peening treatment. The profiles of residual stress distribution are typical both for heat treated and shot-peened surfaces.

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