

X-Ray Diffraction Measurements of Residual Stress Induced by Surface Compressing Methods

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Keywords: residual stress, X-ray diffraction

Abstract

Residual stresses have a fundamental effect on the operational behaviour and lifetime of industrial products. The fatigue resistance of machine parts can be increased by introducing residual compressive stresses into the surface region. For certain machine parts especially in the vehicle industry the residual stress is strongly demanded by the quality control. For this reason, measuring the stress accurately is becoming increasingly important. The Almen test, which only gives a qualitative result, is widely used in the industry. Shot peening and rolling are methods which are suitable for creating elastic residual stresses.

This paper examines the technologies used by Rába Futómű Nyrt. to increase the lifetime by means of residual stress. We performed analysis of the residual stress of samples shot peened the same way but under different heat treatment states. We compared the residual stress values of burnished and hardened shaft joints, and the residual stress states of gear made of hardened alloy, comparing the carbonized ones to ones which were shot peened under small intensity.

Introduction

The processing of machine elements induces a characteristic residual stress field. For example welding, forming, plastic deformation, casting, and any kind of heat treatments [1,2]. This kind of residual stress field sometimes represents a hazard for the lifetime.

Several methods are used in the industry to induce direct compressive residual stress in the surface region of the machine parts to increase the fatigue resistance [3]. Methods which produce residual stress on the surface are called surface-compressing methods, such as shot peening, burnishing and rolling. The value and the distribution of the residual stress which can be induced by these methods depend on many parameters. One of the most important of these is the type of the material. To introduce residual stress into the surface of an alloy, which has low strength is more difficult. In this case the maximum available residual compressing stress is smaller. Moreover, this stress relaxes more easily during the application [4].

Using different surface compression technologies the distributions of the compressive stress under the treated surface can be widely modified with the parameters of the technologies. For example the velocity, the sizes, the hardness of the balls used for shot peening, or the applied force, or tool geometry during burnishing [5,6].

Different procedures evolved to measure residual stress such as the Almen test, hole drilling, ultrasonic, magnetic, Raman spectroscopy, Barkhausen noise methods [7]. Unfortunately, a few gives sufficient deviation and reproducibility while giving qualitative and quantitative results. The Alment strip has been used for more than 60 years in the industrial quality control but quantitative results can be obtained only by the diffraction methods. Disadvantages of the X-Ray diffraction methods include a limited sample size and long measuring time. It is probably the reason that only limited examples can be found about the measurement of residual stress by X-ray in an industrial environmental (large number of samples and short cycle length).

The purpose of this work was (1) to draw attention to the importance of the initial state of a machine part at the surface compression technology; (2) to compare the stress keeping ability of the quenchable steel and the micro alloyed steel for shaft purposes; (3) to show the importance of the

roll burnishing technology and (4) to compare the shot peening and the carburization effect on the surface stress of a gear. The stress results of this article were obtained using X-ray diffraction $\sin^2\psi$ method.

Theoretical basic and experimental setup

Lattice spacing in crystalline materials can be determined by X-ray diffraction analysis. The fundamental equation of X-ray diffraction analysis is Bragg's law, which describes the interrelation between the interplanar distance d , the incident angle θ (angle between the incident beam and the diffracting lattice plane), the wavelength λ of the X-ray used and the order number n of the diffraction.

$$n\lambda = 2d\sin\theta \quad (1)$$

If stress is present, this interplanar distance becomes larger (tensile stress) or smaller (compressive stress). Assuming linear elastic distortions, the related normal stresses can be calculated [8].

$$\sigma = \frac{d_\psi - d_0}{d_0} * \frac{E}{(1 + \nu) \sin^2 \psi} \quad (2)$$

where d_0 and d_ψ are the interplanar distances of unstrained and the strained material (in the tilted position defined by the angle ψ) respectively. E (elastic modulus) and ν (Poisson's ratio) are the elastic parameters of the material.

A Bruker D8 advance X-ray diffractometer equipped with Eulerian cradle and MonoCap primary beam optic with Co $K\alpha$ radiation was used to measure the stress value at the surface layers of the samples. The Eulerian cradle provides the necessary movements (tilting) of the sample holder, while the MonoCap is suitable for the selective area measurements. Fig. 1. represents the diffractometer at $\psi=0$ position. The diffractometer fulfils the qualification and verification requirements of the European standards (ASTM E915-96, CEN/TC 138.[9])

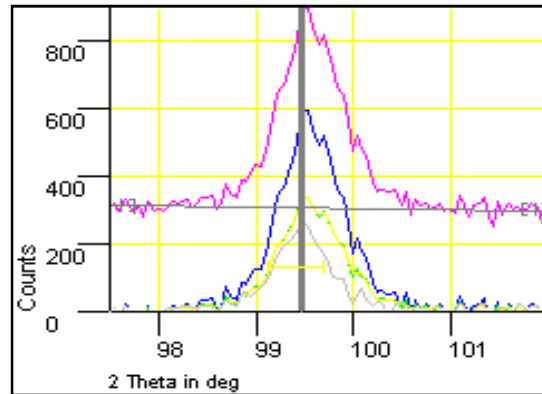
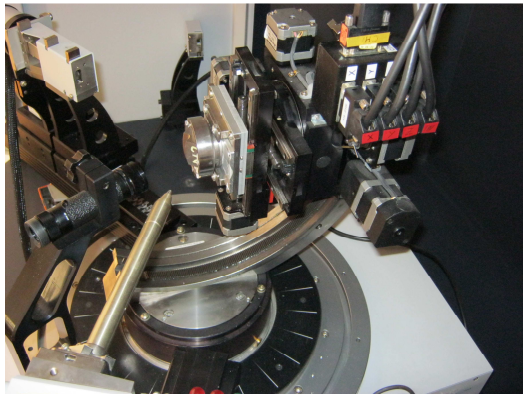


Fig. 1. Bruker D8 Advance diffractometer with Eulerian cradle at $\psi=0$ position and the diffraction profile of (211) plane series after corrections (background subtraction, smoothing, $K\alpha_2$, absorption, Lorentz and polarisation)

Diffra^{plus} Stress (Stress and Edstress) software package was used to determine the stress value from the θ shift of the reflection 211. The 2θ scan interval was $97,5^\circ$ – 102° with $\Delta 2\theta=0,05^\circ$ steps and collecting time of 20 sec. The Bragg position was measured at $\psi = 0^\circ; 10^\circ; 20^\circ; 30^\circ; 40^\circ$ tilting angle. To improve the accuracy of the background subtraction, smoothing, $K\alpha_2$ correction, absorption correction, Lorentz and polarisation corrections were performed (Fig.1.). To determine the exact θ positions of the diffraction peaks for the different ψ angles during the measurements sliding centre of gravity method was used which is preferred in case of industrial products [10].

The test samples were produced in the industrial procedure and they fulfil our goals in many different ways so the materials and the result will be introduced in the next chapter in the order of purposes.

Results

Importance of the initial state of an industrial product

Three different samples of the quenchable 30MnB5 alloy according to the 8EN 10083-3 standard were produced and subsequent shot peening was performed with the same peening parameters. The initial states of the samples are: **1**: hardened (840°C, 1 h), quenched (coolant 10%polimer), tempered (510°C, 0.5 h), and finally the surface decarbonized layer was removed by chemical etching, **2** hardened (840°C, 3 h), quenched, tempered -this causes a wide decarbonized surface layer, **3** hardened (840°C, 1 h), quenched, tempered. Fig. 2. shows the surface roughness after shot peening measured by a laser profilometer that was constructed at the Institute of Material Sciences, and the Fig.3. shows the average residual stress value.

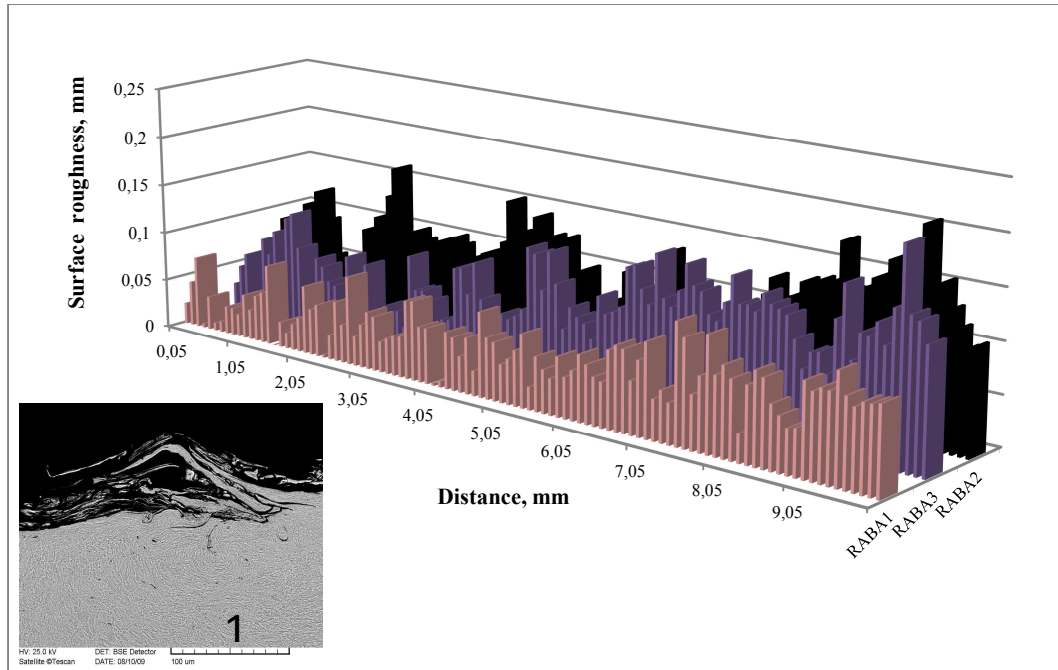


Fig. 2. Roughness and a SEM image about the surface quality after shot peening

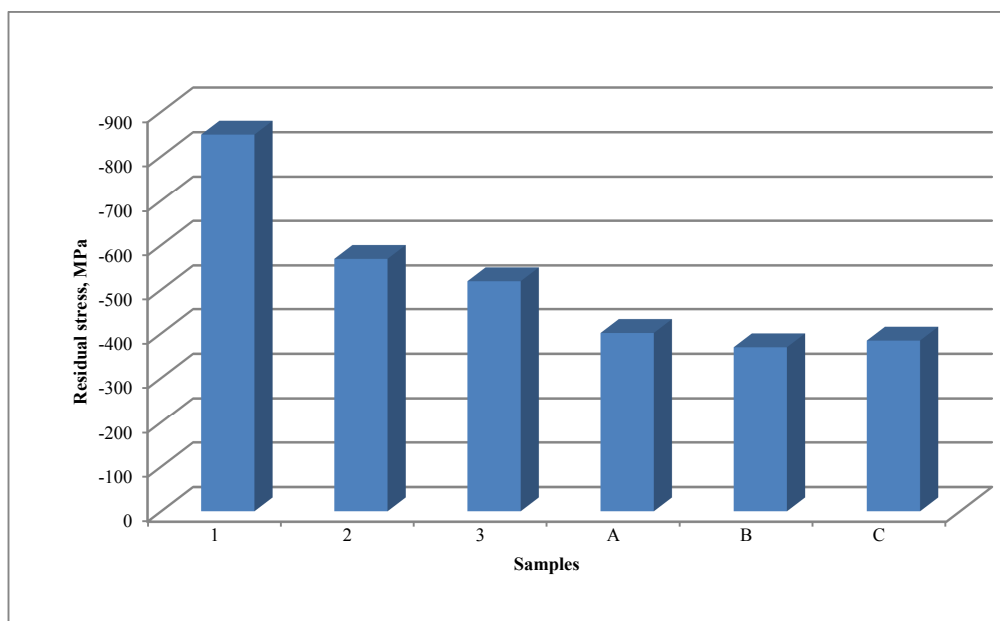


Fig. 3. Residual stress on the surface

It can be seen from Fig. 2. that the sample with a thick decarbonized layer (2) has a strong scatter in roughness, while sample 1 has somewhat smaller but also does not have a smooth surface. It shows bigger compressive stress than the decarbonized (having smaller yielding stress) samples. The difference is very remarkable (Fig 3.).

Quenchable versus micro alloyed steel for shaft purposes.

Micro alloyed steel is an economically good candidate to replace heat treatable steel in the vehicle industry. Three micro alloyed (ZF59 according to the EN 10204 3.1 standard) samples were prepared for a comparative analysis. The micro alloyed samples are the following. **A**: heated once to austenitic temperature, **B**: heated two times to austenitic temperature and **C**: heated three times to austenitic temperature. All of the samples were forged and subsequent shot peening was performed with the same peening parameters than in case of samples 1, 2, 3. In Fig. 3. the comparative results are shown. The micro alloyed samples have 50% lower compressive stress than the hardened and tempered ones, but this alloy is less sensitive to the decarbonization so the stress value is very similar in the three samples (A,B,C). The roughness differences were also measured in these samples, the results are shown in Table 1.

Table1. Correlated roughness of samples 1-C

Samples	Roughness normalized to the sample No1[-]
1	1
2	7
3	1.8
A	2.1
B	2.9
C	2.7

Applying the roll burnishing technology

The joining points of the shaft with different diameters are known to be risks for the crack formation and propagation. Increasing the radius of the joint point the risk of cracking can be decreased. The fatigue life time can be increased by inducing a compressive residual stress at this part of the shaft. Applying an appropriate compression load a subsequent a compressive residual stress is formed. Samples were prepared using roll burnishing technology. [11.] During the burnishing 5200 N pressing force, about 84 1/min engine speed, 40 sec/ surface treating time, and OMV CUT XU coolant were applied. Stress measurements were also performed on samples from hardened, and hardened plus burnished shaft joints made of steel (CrMo 35). Residual stress analyses were performed on the internal fillets of the samples. Two parallel measurements were performed on each sample. Two shafts with different radii of internal fillets were examined in hardened plus burnished states. The two different inner radii are denoted as r and R . The notations 1 and 2 denote the parallel samples. The experimental setup and the difference of the hardened and of the hardened plus burnished samples are shown in Fig. 4.



Fig. 4. Experimental setup of roll burnishing, parts of the hardened and the burnished samples

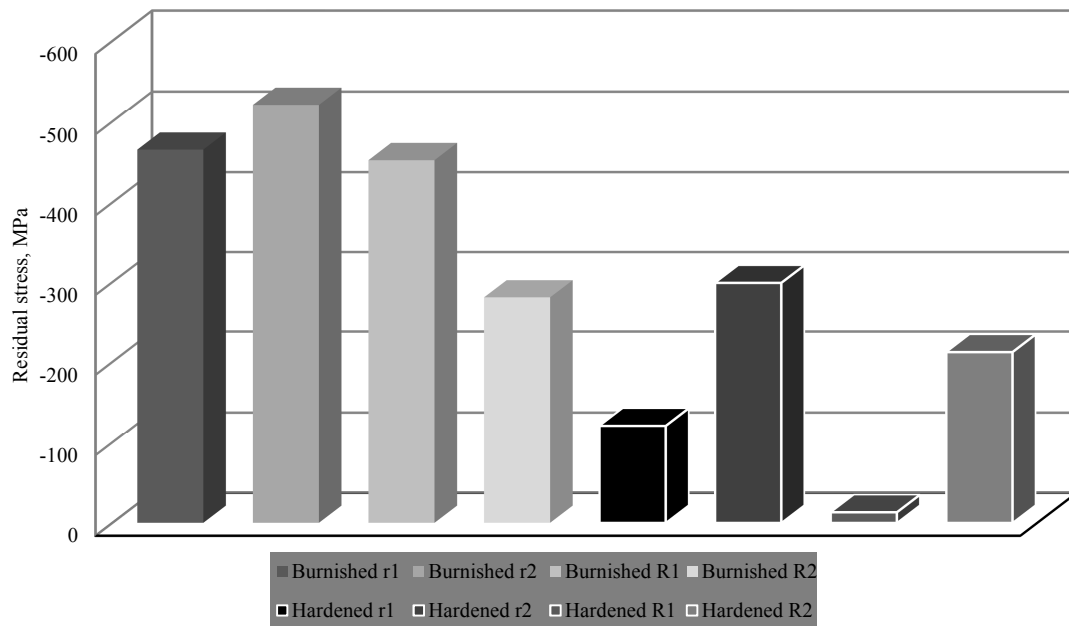


Fig.5. Residual stress values on the surface of shaft joint samples

The effect of roll burnishing is evident. The compressive stress level value can be doubled compared to the only hardened ones (Fig.5.). The residual stress values of the hardened samples are scattered. This effect is originated from the low value of signal to background ratio. Near to the zero stress level the uncertainty extends.

Shot peening versus carburization on the surface of a gear

The comparison of the residual stress values of the carbonized and the shot peened gear samples are shown in Fig. 6. The surface roughness determined by stereo microscopy (magnification is about 100x) is also shown on the front panels of the figure marks. The intensity of the shoot peening was much lower than in the previous cases so the roughness is identical. Although the primary object of carbonizing is the surface alloying, this treatment has another remarkable property. The introduced residual stress in the surface layer is compressive and has a double value than the other one.

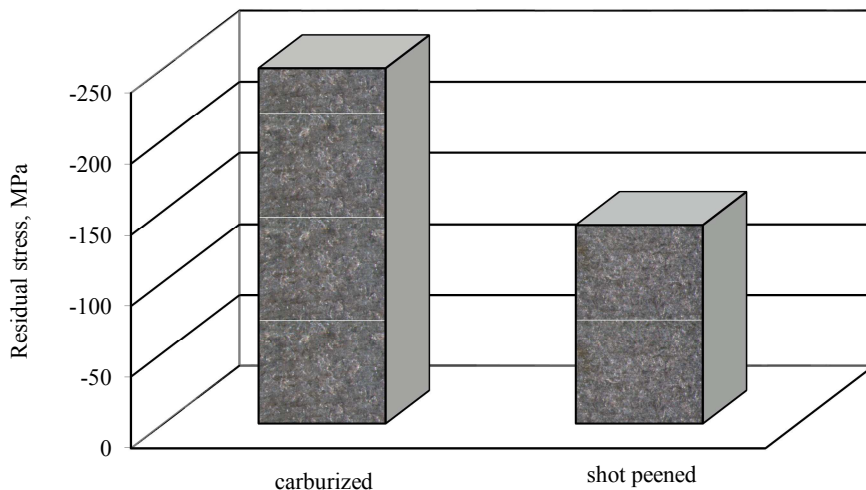


Figure 6. Residual stress values on the surface of gear

Summary

The literature explains the effect of the parameters of surface compressing for a given alloy, for example, grain size and speed, the peening intensity on the stress both on the surface and the under the surface. However, the amount of the residual stress is influenced by other factors too. Our research was focused on the effect of the technological record of the treated parts (i.e. heat treatment state, technological irregularity, material quality) on the resulting stress field.

In our first series of experiments, we examined the surface region stress of a hardened steel shaft (Rába Futómű Nyrt) as a function of the amount of decarbonization. We have shown that the surface stress values vary significantly with the thickness of the decarbonized layer. During our further experiments, we compared the stress keeping ability of the micro-alloyed steels designed as a substitute for the quenchable alloy used in the vehicle industry. The big advantage of the roll burnishing was also shown at the different radii of an internal fillet made of quenchable alloys. A well defined compressive stress was measured after the carburization and the shot parameter sensitivity of the shot peening is also confirmed.

The measurement of the residual stress was carried using a Bruker D8 Advance X-ray diffractometer equipped with an Eulerian cradle.

Acknowledgements

The described work was carried out as part of the TÁMOP-4.2.1.B-10/2/KONV-2010-0001 project in the framework of the New Hungarian Development Plan. The realization of this project is supported by the European Union, co-financed by the European Social Fund. The authors of this paper would like to thank Á. Kovács, for the SEM pictures, J. Sólyom for the valuable discussion, A Rónaföldi for the laser profilometer and M. Losonczy for his help in sample preparation.

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