

UNIVERSITY OF DEBRECEN
Faculty of Engineering
Department of Mechanical Engineering



PROCEEDINGS OF THE
5th INTERNATIONAL SCIENTIFIC CONFERENCE ON
ADVANCES IN MECHANICAL ENGINEERING
(ISCAME 2017)

12-13 October, 2017

Debrecen, Hungary

organized by

Department of Mechanical Engineering
Faculty of Engineering, University of Debrecen

and

Working Commission in Mechanical Engineering
Specialized Committee in Engineering
Regional Committee in Debrecen, Hungarian Academy of Sciences



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Publisher: **Department of Mechanical Engineering**
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 Web page: old.eng.unideb.hu/gepesz

ISBN 978-963-473-304-1



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RESIDUAL STRESS MONITORING FOR MACHINE INDUSTRY

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Abstract

Determination of the residual stress state is highly important because it has a strong effect on the lifetime of the component and it can cause deformation or failure during the manufacturing. Nowadays, the residual stress characterization became an everyday requirement in the machine industry. Several methods exist for measuring the residual stress, with this paper our purpose is to introduce the non-destructive residual stress measuring by XRD, and show quantitative characterization and results from the machine industry. Two examples are presented about the stress monitoring during the manufacturing, while one is during fatigue test.

Keywords: *Residual stress, Non-destructive measurement, XRD, Fatigue*

1. INTRODUCTION

Forasmuch as every producing process (casting, heat treating, different kinds of metal deformation processes and surface compressing methods, etc.) influences the residual stress state, therefore it can be very complex and various within the materials [1,2]. If we conscious in the effect of these processes it is possible to reach such a state in the material which can enhance its lifetime and quality, and with an optimized process, the costs could be reduced [3-5]. In this manuscript a series of residual stress measurements using X-ray diffraction were performed with different purposes. One example shows the importance of the residual stress evaluation during the whole process line the other example shows the evidence about the relationship between the stress state and the manufacturing scrap.

2. METHODS

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 wave length 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:

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

where d_0 and d_{ψ} are the interplanar distances of the strained material in the normal and in the tilted position defined by the angle ψ respectively. E (Young modulus) and ν (Poisson number) are the elastic parameters of the material. The present manuscript gives an overview on the measurement possibilities by an innovative equipment of the Institute of Physical Metallurgy, Metalforming and



Nanotechnology at the University of Miskolc. The equipment is a Stresstech Xstress 3000 G3R type X-ray diffractometer developed especially for non-destructive residual stress measurements. The presented diffractometer has a remarkable innovation compared to the traditional ones. In the case of traditional diffractometers the sample is tilted by precision mechanics. The revolutionary construction of the G3R tilts the device instead of the specimen, which allows measurements without sample cutting, so the true stress state of the component is unaffected. Furthermore, there are no sample size and weight limits for the measurements [6]. This method provides residual stress values from 10 μm depth of the surface layer (depending on material type, applied generator power, Bragg-angle). A Cr radiation was used to measure the {211} reflections of the samples. For stress calculations, the following material constants were used: Poisson's ratio $\nu = 0.3$, Young's modulus $E = 211000 \text{ MPa}$. The measured parameters (the investigated variables) such as maximum tilting angle, the number of tilting and spot size (the diameter of the beam on the examined surface) were changed during the test. The exposure time was chosen based on the requirement of proper signal/background ratio, so it was changing, and it is given at the presence of results chapter.

3. RESULTS AND CONCLUSIONS

The reproducibility of the XRD measurement is shown in Fig.1. The measurements were done 10 times on the shot peened surface of a steel component, without changing the parameters or the position of the sample. We can state that the value of standard deviation is excellent.

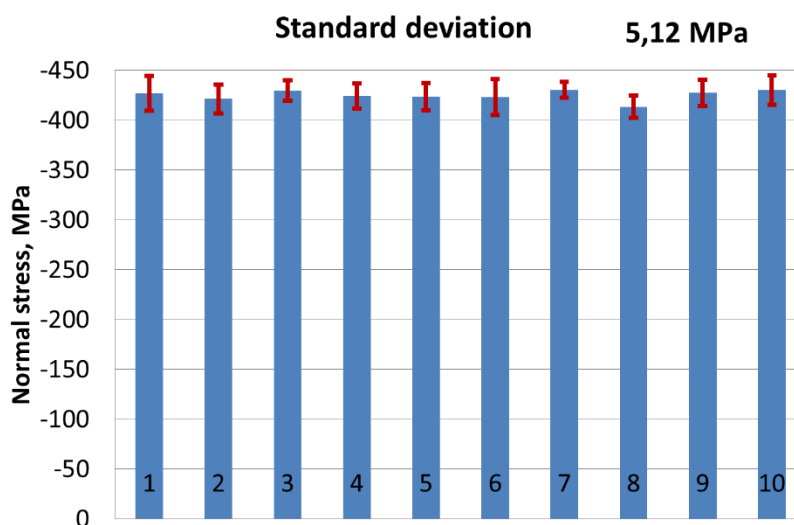


Figure 1 Reproducibility of the stress measurements on the shot peened steel surface

Stress monitoring during the process

The examined bearing rings were made of 100CrMn6 alloy according to the EN ISO 683-17 standard. The outer and the inner rings were evolved from a common semi-product. The first step of the process was hot forging at 1190°C. The next step was the turning. This was followed by the severing and the separation of the inner and outer rings. After severing, the rings were hardened at 835°C for 40 minutes then cooled in a 190 °C salt bath and a subsequent tempering at 200°C for 25 minutes was done. Finally, the hardened rings were finish-grinded. The stress states were measured after the hot forging (1. process), the turning of outer ring (2. process), severing (3. process) and heat treatment (4. process). The tangential residual stresses were measured at 12 positions (labelled from 0 to 11) on the middle perimeter of outer rings. The locations of the 12 measured positions were the same after each technological step. Data were recorded in 5 tilting positions in Ω mode in



the -35° to 35° interval with 10 sec exposure time and 1 mm spot size. The state of the rings after the different process steps, the measured position and the results are shown in Fig. 2. Scatter of the measurements never exceeded ± 20 MPa, therefore they are not marked. The measured residual stress values of the rings after the 1st processing step is compressive. Due to turning (2. process), the compressive stresses of the ring changed to intensive tensile stresses. The severing (3. process) did not make any detectable changes in the stress state, while the heat treatment (4. process) induced a near stress-free, relaxed condition. It is evident that the stress values of the rings vary between 600 and -200 MPa during the processing line. Even the final stress state is quite convenient if the distortion or microcrack have formed after turning due to the high tension stress those are unchanged and still exist after the heat treatment. So it is a typical example that the stress state control at the final state is not sufficient to detect the reason of failure of a component.



1.process



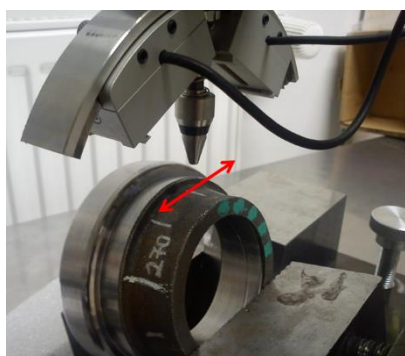
2.process



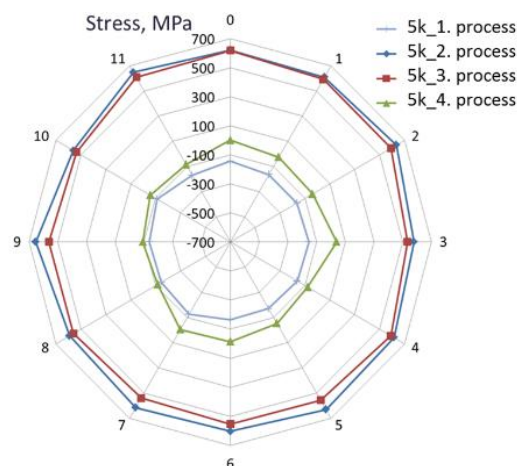
3.process



4.process



measured stress direction



stress distribution

Figure 2 Stress distribution of the bearing rings after different process steps.

In case of other example residual stress measurements were carried out during the finishing manufacturing technology steps (hardening, grinding, shot peening) of spiral bevel gears to see through the evolution of the residual stress during the full manufacturing. The examined component is prone to fracture during straightening after the hardening heat treatment. The aim of the stress monitoring is to find out the role of residual stress in the component's failure. The measurements were performed using 3 tilting positions in both $\pm$ directions. The measurements were carried out on two components, having the same history of production. One of the components had eccentricity values within the tolerances of the manufacturer (labelled as "good" component), while the other one had eccentricity outside the tolerances (labelled as "bad" component). The measurement locations were determined at two spots critical from the aspect of the component, on the six tooth tops and on the axle part, where occasional fracture typically occurred. The measurements were carried out in two different measurement directions (axial, tangential) in each point as shown in Fig. 3.



Based on the stress measurement results, there is no difference between the "good" and "bad" components tooth tops neither in axial nor in tangential directions. On both components, the stress distribution is uniform and the stress values are similar. In forged state, the measured stresses are compressive, which turned into tensile after machining. After hardening, the stress state changes in general. Grinding had no major effect on the tooth top and the shot peening step increased the already existing compressive stresses, as it was expected. The stress evolution during the full manufacturing changes between 600MPa and -500MPa as it is shown in Fig.3. The measured stresses on the axle indicate that there is a difference between the stress values of the "good" and "bad" components. The stress distribution is irregular in both components. The stresses are compressive in nature after the various technology steps. The values change between 0MPa and -700MPa. So the stress asymmetry was calculated. From the aspect of bending, the critical stress component is the axial stress of the axles. Thus, stress asymmetry was calculated only in the axial direction. The stress asymmetry results are shown in the Fig.4. Since stress state prior to hardening is relaxed at the austenization temperature, stress asymmetry was calculated only for technology steps after hardening. After hardening, the maximal value of stress asymmetry of the "bad" component is about 200 MPa, while that of the "good" component barely reaches 100 MPa. It is important to note that the maximal stress asymmetry occurs in the plane of measurement points 5 and 11. In grinded state, the plane of the maximal stress asymmetry is still the plane of the points of 5 and 11. The plane of the high stress asymmetry matches with the plane of measured highest eccentricity. Thus, stress asymmetry is proven to be suitable to characterise the component's bending stress.

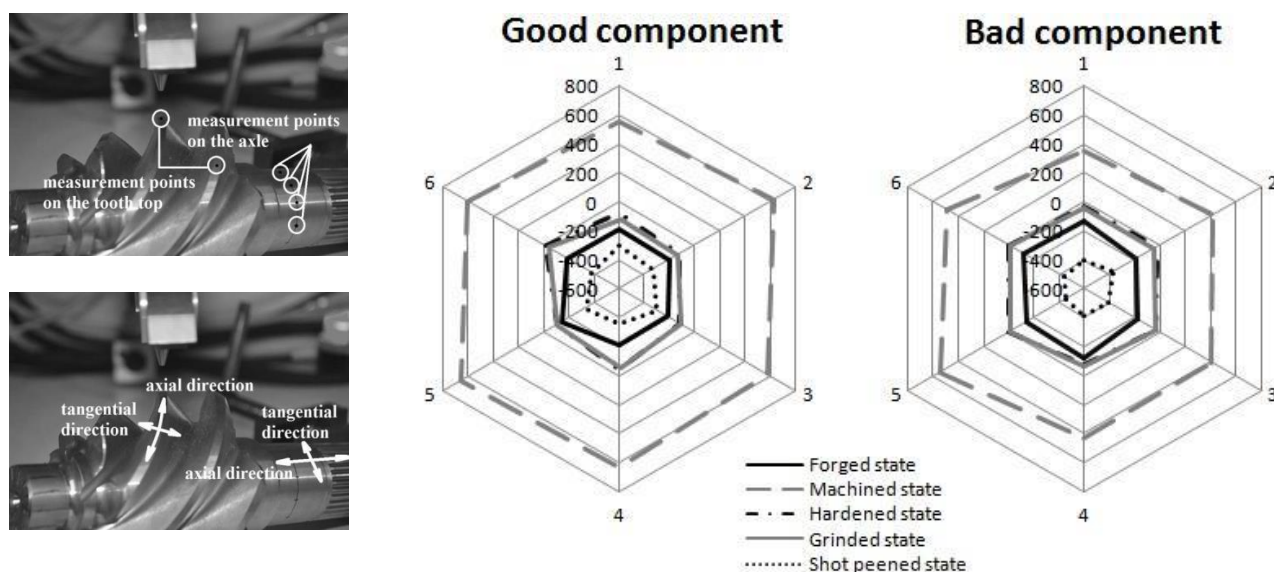


Figure 3 The measured points and directions and the variation of stress distribution on the tooth tops after the examined technology steps. Axial stress components

Stress monitoring during fatigue

The stability of surface compressive residual stress on hardened, shot peened 42CrMo4 steel specimens during fatigue load was investigated. This is a widely used steel in the vehicle industry especially in the case of surface compressed machined elements. The residual stress state of machine elements can change during application, therefore it is necessary to describe how these changes are related to the operational parameters. The residual stress state was recorded in shot peened state and monitored during the fatigue tests. The fatigue test was stopped after certain cycles until the specimens fractured. The stress state was measured after each fatigue test stops and the



stress relaxation is given in the percentage of the initial stress state in function of cycle number. The specimens were induction hardened and oil quenched. To measure the temperature of the specimens and to control the inducer, Ni-NiCr thermocouple was soldered to the surface. First, the specimens were rapidly heated to 1000°C during a few seconds then the temperature was held for 2 seconds. When the sample reached 850°C, the thermocouple was cut from the specimens and the specimens were immersed in quenching oil media. During the immersion the longitudinal axis was perpendicular to the surface of the media. The tempering was carried out at 600°C in an inductive furnace for half an hour, and specimens were subsequently cooled in air. The shot peening was performed at the Rába Automotive Holding Plc. This means that the parameters of the applied peening method were industrial parameters. The peening time was 9 minutes. Two Almen C strips were fixed on the sample holders to control the peening. The values of the Almen C probes were 0.26 and 0.24. The used peening balls were made of 1.8 mm diameter steel wire (430 HV), cut in 1.8 mm length pieces and conditioned for 4 hours. The minimal peening coverage was 150%. The average speed of the balls, which left the peening wheels was 55 m/s. As an average 117 J/mm² energy was imparted with the surface.

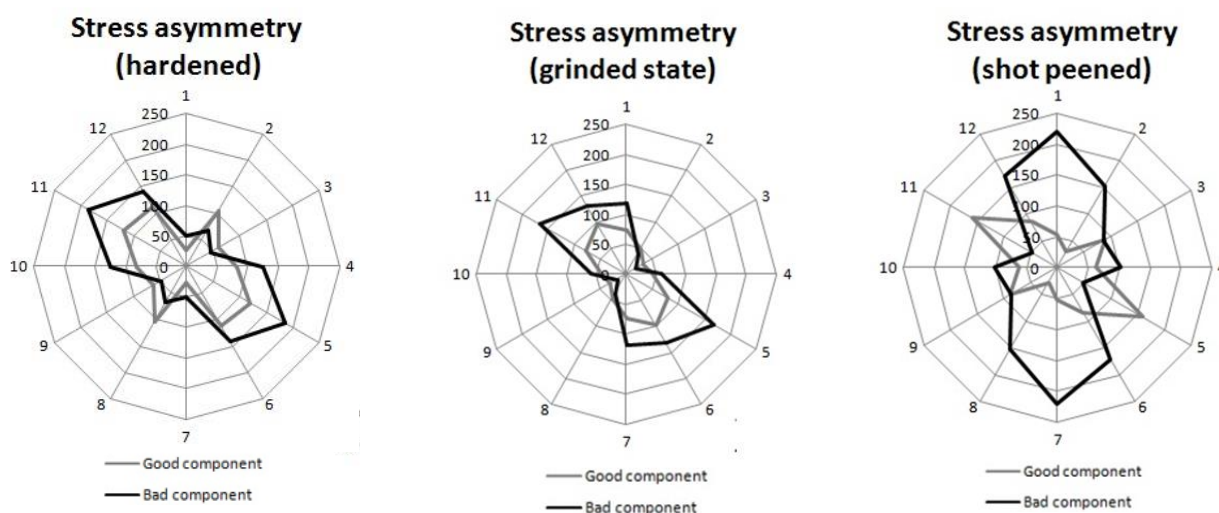


Figure 4 Stress asymmetry calculated after the different technological steps along the critical circumference of the axle. Axial stress component.

The residual stress was calculated according to the $\sin 2\psi$ method. Reflections were obtained in ψ geometry from 3 tilting positions in the $-45^\circ/+45^\circ$ range. The axial residual stress state was recorded at 3 spots with 3 mm spot size areas, on each side of each specimen in the initial shot peened state and during the fatigue loads. The same areas were investigated in each step of the monitoring. The sample geometry was quadratic (7x7 or 5x5). The stress was measured with less error (scatter) than ± 10 MPa in every point. The fatigue load was tensile-compressive, the stress ratio ($R\sigma$) was -1 ($R\sigma = \sigma_{\min}/\sigma_{\max}$; $\sigma_{\max} = 350; 500$ MPa); so the absolute values of the tensile and compressive stresses were equal. The cyclic load was implemented by an MTS type universal electro-hydraulic testing machine of the Institute of Materials Science and Technology at the University of Miskolc. The Fig. 5 shows the results. The sample marked with H was only hardened, so the enhanced lifetime due to the shoot peening is evident. The significance of the fatigue stress amplitude is multiple: the higher stress level results shorter lifetime, and higher extent of residual stress relaxation. No systematic effect is connected to the sample size. The stress relaxation rate shows an increased level by increasing the fatigue stress amplitude. It is evident that the rate of the stress relaxation is very fast in the first thousand of the cycles.

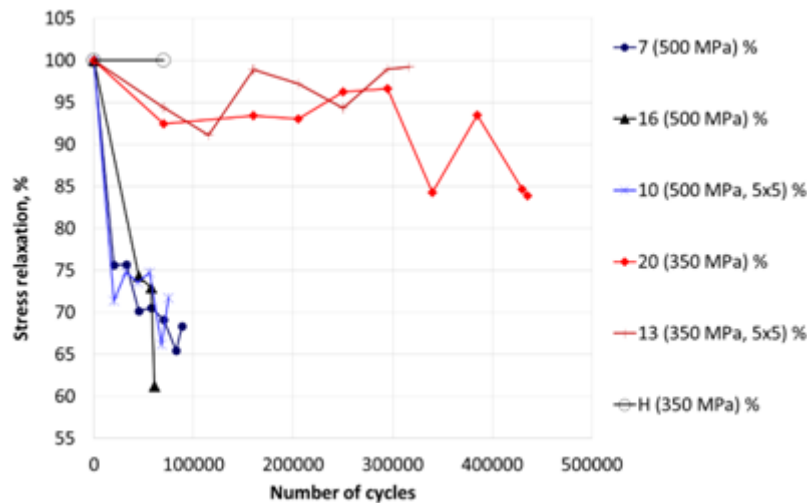


Figure 5 Compressive stress relaxation during fatigue at 500 and 350 MPa stress level.

SUMMARY

Monitoring the residual stress evaluation of a spiral bevel gear and bearing rings during manufacturing were performed. The stress varied in a very wide range even from -100 MPa compression to the 600 MPa tension between the different manufacturing steps. It was experimentally shown that the high stress asymmetry matches with the plane of measured highest eccentricity. Thus, stress asymmetry is proven to be suitable to characterise the component's bending stress. Compressive stress relaxation after shoot peening was also investigated during fatigue. It was stated that the higher fatigue stress amplitude indicates larger extent of residual stress relaxation. The absolute value of the initial residual stress state does not have systematic effect during the relaxation. The higher relaxation has no correlation with the value of the initial residual stress.

ACKNOWLEDGEMENT

This research work was supported through the New National Excellence Program of the Ministry of Human Capacities.

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