

## **Monitoring the residual stress evolution of a spiral bevel gear during its manufacturing steps**

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### **ABSTRACT**

Nowadays, it is generally recognized by the members of automotive industry that residual stress can have notable effect on the products' quality and/or lifetime. Because of that, more and more attention is paid to get to know the residual stress states of the automotive components in the final state and during the manufacturing processes as well. In this paper the residual stress state variation of spiral bevel gears were examined after the main manufacturing steps. The residual stress was measured at two critical locations, the tooth tops, and the axle, where the occasional fracture of the components occurred. Owing to the non-destructive type of the applied residual stress measurement technique, the measurements were performed on the same components after the manufacturing steps. Based on the results, the occasional bending and fracture of the components were connected to the stress asymmetry arisen in the components after hardening heat treatment.

### **INTRODUCTION**

Residual stress is always introduced into machine elements and can either be useful or harmful depending on the type (compressive/tensile) and magnitude. If compressive residual stress is arisen within a component at defined locations, crack propagation can be exhibited, thus, the resistance against fatigue will be increased. Because of that, some techniques, such as shot peening, or ball burnishing were developed to increase the components' lifetime [1]. However, there more situations when residual stress causes failure by undesired deformation or crack formation. After all, knowing the type and magnitude of residual stress of machine components is fundamental for the production industry. For some manufacturing methods, the type of the introduced residual stress is relatively easy to predict. For example, during forging the component is forced into a form which causes compressive stress in the entire component. However, for most of the manufacturing methods (machining, turning, heat treatments, etc.), the formed stress state is much more complicated [2-6]. Furthermore, since residual stress states of the different subsequent processing steps interfere, the resulting stress state of a component can be extremely diverse depending on the processing parameters. Monitoring the formation of residual stress state of a component during the main processing steps can reveal sources of failures.

In this paper, 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 (Fig. 1). The aim of the stress monitoring is to find out the role of residual stress in the component's failure.



Figure 1. The examined component and the critical area prone to fracture [1]

## EXPERIMENTAL

The examined spiral bevel gears were produced by Rába Automotive Holding Plc. The main technology processes are forging, machining, hardening, grinding and shot peening. The components were delivered to the University of Miskolc after each technology processes to perform the residual stress measurements. Once the measurements were carried out, the components were sent back the manufacturer to perform the next processing step. Thus, the residual stress variation during manufacturing was monitored on the same components.

The X-ray diffraction measurements were carried out by non-destructive Stresstech Xstress 3000 G3R equipment. The measurements were performed using Cr X-ray source, 3 tilting positions were used in both  $\pm$  directions. The shift of the  $\{211\}$  reflection was measured and Young-modulus: 211000MPa and Poisson's ratio of 0.3 was used to calculate stress [7].

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 (Fig. 3a). The measurements were carried out in two different measurement directions (axial, tangential) in each point as shown in Fig. 3b.

For pure bending, there is a tensiled and a compressed generatrix in the axial direction. However, if the stress state is more complex by adding a uniform additional compressive stress, the stress of the tensiled generatrix is decreased, furthermore, it can even be neutral, while the stress of the compressed generatrix will be increased. In a general stress state, the bending stress is given by the stress asymmetry and can be calculated as the difference of stress state of the opposing

generatrix. From the stress distribution along a circumference the stress asymmetry was calculated to characterise the component's bending stress.

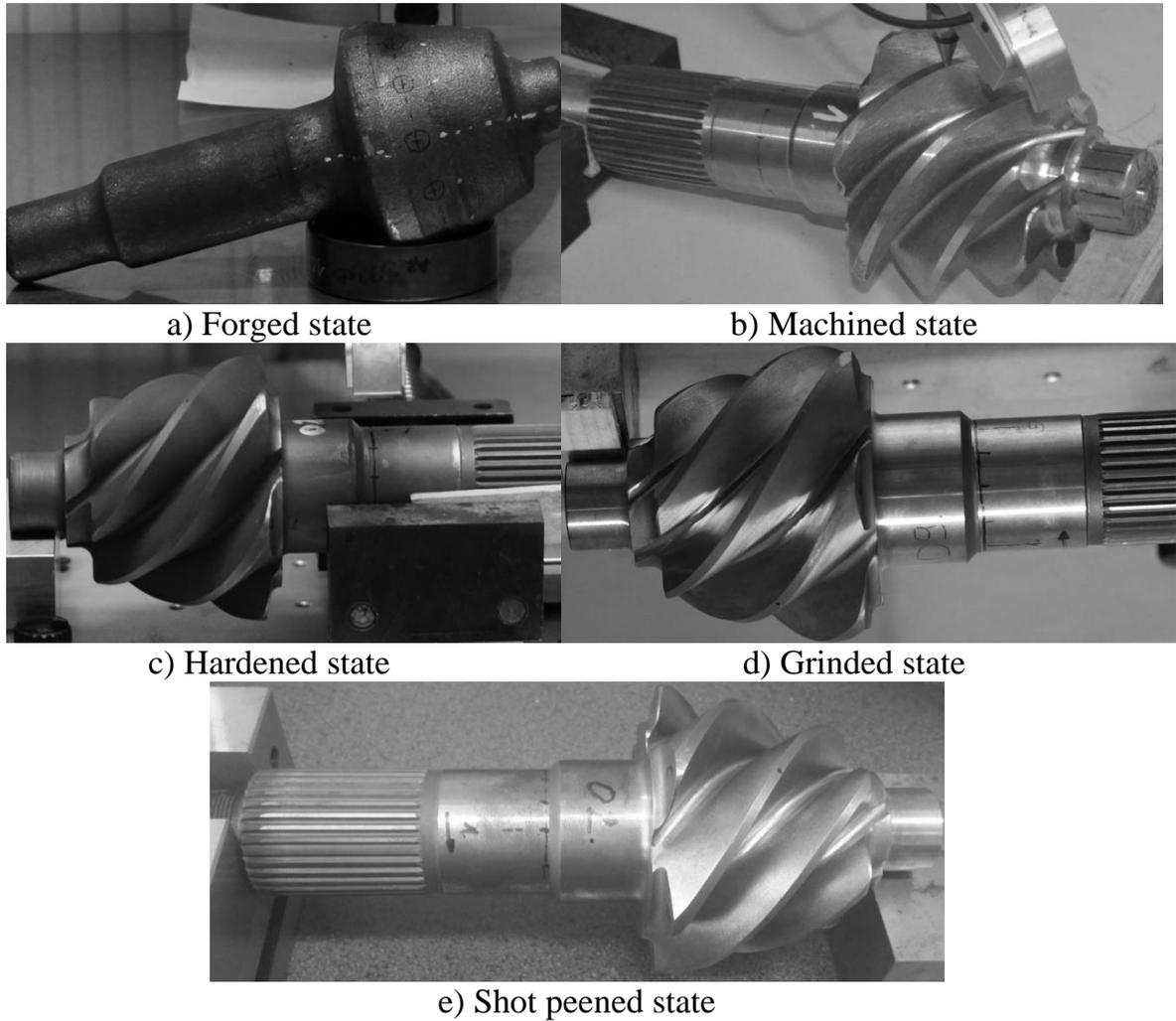


Figure 2. The examined component in five different manufacturing states

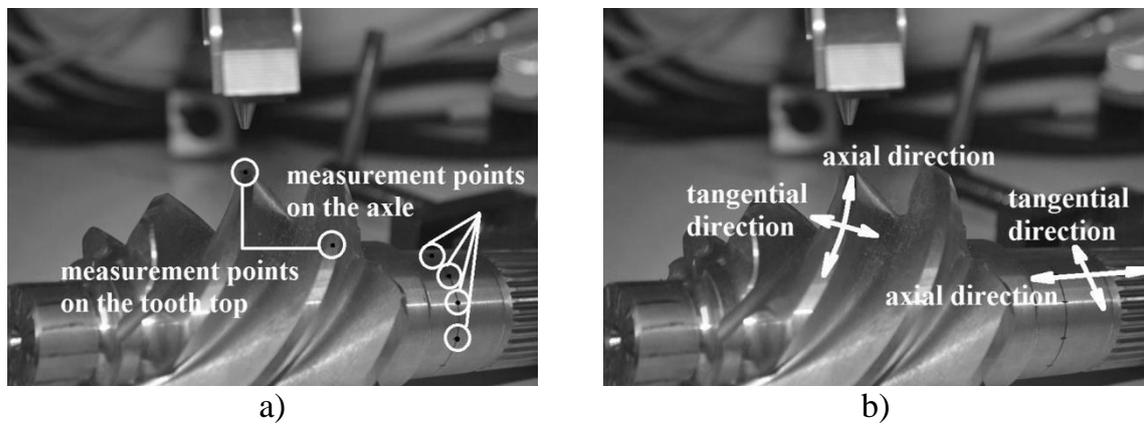


Figure 3. The measurement points and directions of the cone-wheel in machined state

## RESULTS

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 Figure 4 and 5.

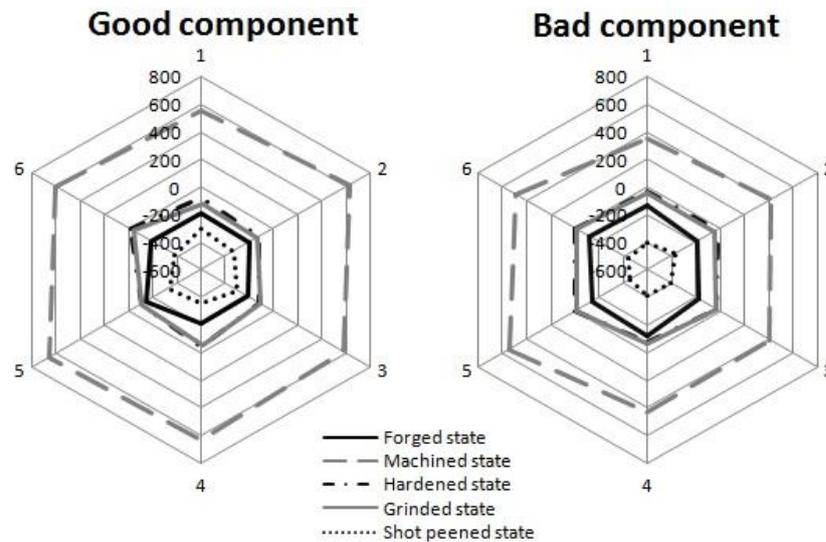


Figure 4. The variation of stress distribution on the tooth tops after the examined technology steps. Axial stress components.

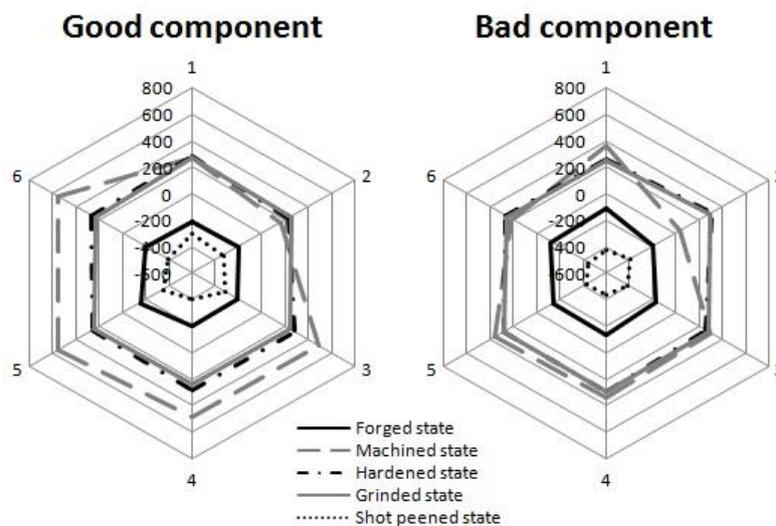


Figure 5. The variation of stress distribution on the tooth tops after the examined technology steps. Tangential stress components.

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, shown in Figure 6 and 7.

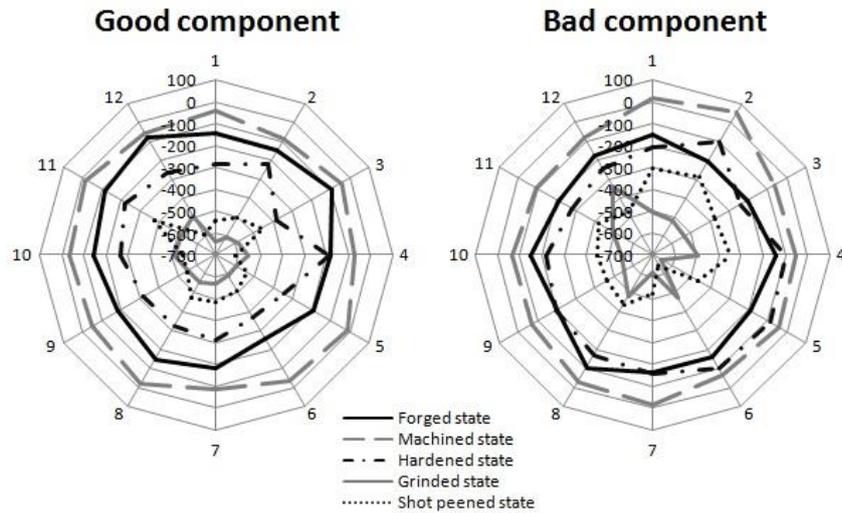


Figure 6. The variation of stress distribution along the critical circumference of the axle after the examined technology steps. Axial stress components.

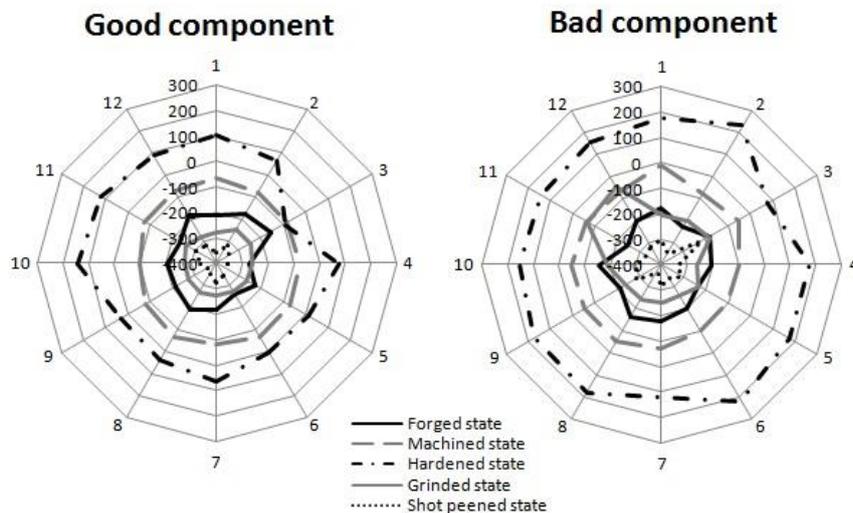


Figure 7. The variation of stress distribution along the critical circumference of the axle after the examined technology steps. Tangential stress components.

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 Figure 8, 9, and 10. Since stress state prior to hardening is relaxed at the austenization temperature, stress asymmetry was calculated only for technology steps after hardening.

As Figure 8 shows, after hardening, the maximal value of stress asymmetry of the "bad" component is about 200MPa, while that of the "good" component barely reaches 100MPa. It is important to note that the maximal stress asymmetry occurs in the plane of measurement points 5 and 11. The scatter field figure shows that the measured stress values are correct, as the maximum of the scatter is  $\pm 50$ MPa.

In grinded state (Figure 9.), the plane of the maximal stress asymmetry is still the plane of the points of 5 and 11, although high values can be seen in the plane of points 1 and 7. As the measurement scatter shows, the point 5 has a large scatter value ( $\pm 250$ MPa), therefore, the measured stresses in this plane are not accurate. (It was proven by control measurements that the high scatter in this plane originated from the heterogeneous stress state of the component, and not from measurement inaccuracy.) Note, that the plane of the highest asymmetry in hardened state and the plane of the highest scatter after the following manufacturing step coincide.

In shot peened state, the plane of points 5 and 11 has no stress asymmetry. The highest stress asymmetry is in the plane of points 1 and 7, with a value of 200MPa. In the scatter field function (fig. 8) we can see again, that the planes with previous maximal asymmetry have high scatter.

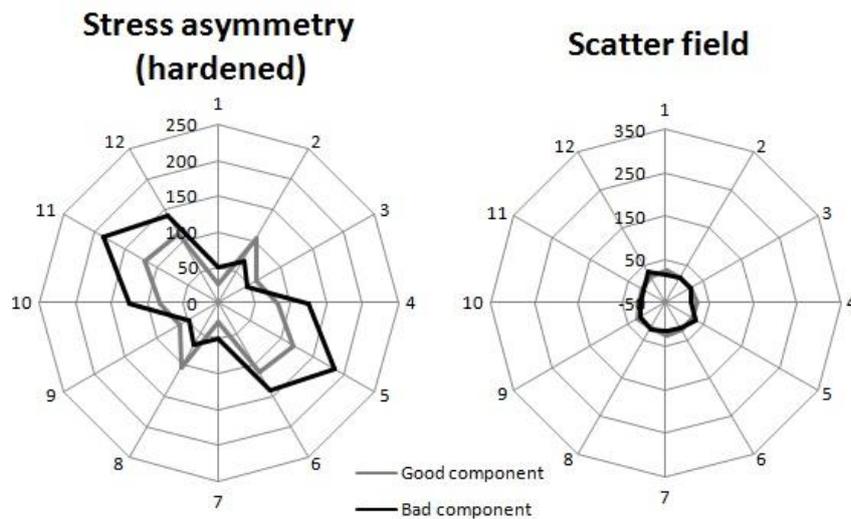


Figure 8. Stress asymmetry and measurement scatter in hardened state

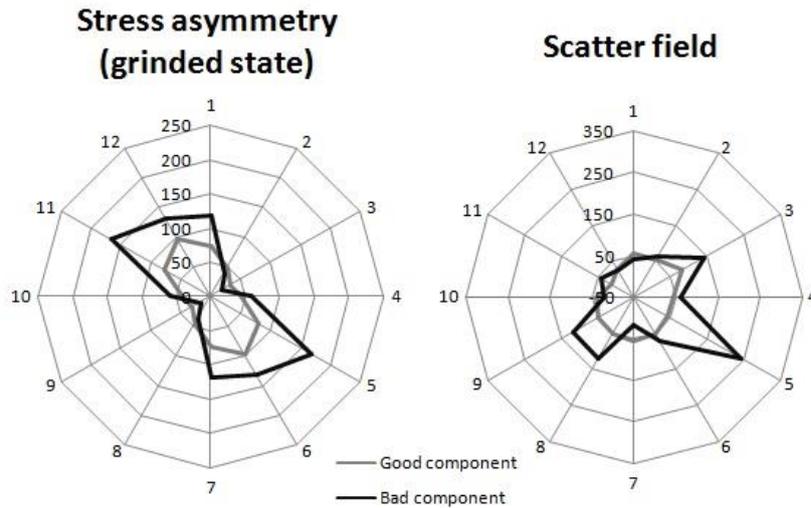


Figure 9. Stress asymmetry and measurement scatter in grinded state

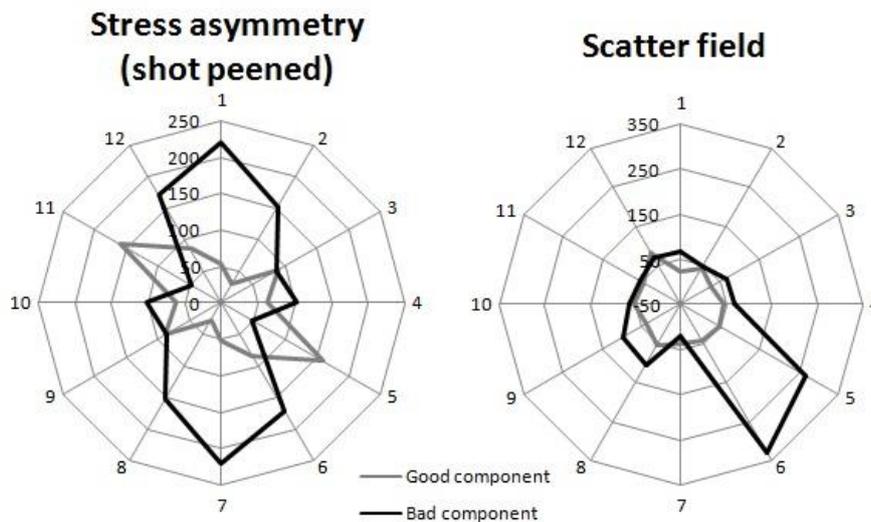


Figure 10. Stress asymmetry and measurement scatter in shot peened state

## SUMMARY

The stress measurements on the tooth tops indicate no difference between the “good” and “bad” components in axial or tangential directions. The stress distribution is consistent and the stress values are very similar. The type of the stress strongly depends on the type of process steps. The stress state of the examined components varies within a wide range of 600MPa and -500MPa.

On the other hand, on the axle, a notable difference was seen between the “good” and “bad” components. For the “bad” component, the stress distribution is irregular in the critical direction (axial direction, responsible for bending). Accordingly, the stress asymmetry is only about 120 MPa for the “good” component, and the measured eccentricity was within the tolerances, while stress asymmetry is about 200 MPa for the “bad” component and a notable eccentricity

was measured. 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.

The plane of the stress asymmetry changes after the following processing steps. The reason of this is still to be examined.

## **ACKNOWLEDGEMENTS**

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