PROCEDURE FOR NONDESTRUCTIVE RS-MEASUREMENTS OF INNER SURFACES OF BALL BEARING COMPONENTS

Jérémy Epp, Thomas Hirsch
IWT- Stiftung Institut fuer Werkstofftechnik, Bremen, Germany

ABSTRACT

Machining induced residual stress states contribute to the distortion of machined components during heat treatments. Thus, ideally a complete characterization of the components residual stress state is required. Magnetic and micromagnetic analysis of residual stresses can represent an important gain of time if compared to X-ray diffraction. Another important advantage is the access of inner faces of components like ball bearing rings. This study presents a comparison of these two methods for the characterization of outer and inner surfaces of ball bearing rings. A good calibration of micromagnetic measurements with X-ray diffraction data is necessary. Reliable results then can be achieved and the residual stress states of rings can be characterized. Effects of clamping systems and feed on the residual stress levels and distribution will be discussed, as well as complex interactions. An implementation of the presented micromagnetic method for non-destructive control in large manufacturing series could be possible.

INTRODUCTION

In the Collaborative Research Centre SFB 570 “Distortion Engineering” problems of distortion as a system property of the whole manufacturing process of components have been studied since 2001. On the basis of many experimental results as well as of computer simulations, it was found that machining induced residual stresses are one of the main distortion causes [1 -3]. Moreover, prior studies have shown that especially the different machining parameters for the production of rings have an influence on residual stress fields. Parameter variations during machining consequently affect distortion significantly [2- 4]. For the evaluation of residual stress effects on the distortion potential, a complete characterization of machined parts with several dozens of residual stress measurements is necessary. X-ray diffraction is a state of the art measurement method of residual stresses and its use is already well established in the research field but also industrially. However, this technique has disadvantages. Firstly, a reliable measurement of one residual stress component with a conventional X-ray diffractometer takes from 10 minutes to several hours. A complete biaxial surface residual stress state characterization of a component then will take some days. Secondly, the measurement of the inner face of tubes or rings, is difficult or even not possible. As a consequence, the use of other techniques with an important gain of time and a better accessibility is required.

Non-destructive micromagnetic methods for residual stress measurements have been developed in the last three decades [5 -7]. These techniques are mainly based on the analysis of the Barkhausen noise. Alternative methods consist of the analysis of several micromagnetic parameters like magnetization, analysis of eddy currents, Barkhausen noise, incremental permeability and dynamic magnetostriction [5]. The principle of these analyses is based on the interaction of residual stress fields with the movement of domain walls, also called Bloch walls, and with domain rotations during the magnetization processes [5, 8]. One difficulty
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arises from the fact that not only stresses influence the measurements but also the microstructure like phase and grain boundaries, inclusions, dislocations, and other defects change measured micromagnetic parameters [5 -7]. A careful calibration is therefore required. Previous work showed that a comparison between results of X-Ray diffraction data and measurements of magnetic and micromagnetic properties of materials depends on the calibration procedure [9].

In this study, a procedure for the measurement of residual stresses on the outer and inner faces of bearing rings with a micromagnetic method has been tested. Results have been compared with X-ray diffraction data. Furthermore effects of machining parameters on residual stress states will be demonstrated.

**EXPERIMENTAL PROCEDURE**

The present study has been performed with cylindrical ball bearing rings. The steel grade was the bearing steel AISI 52100 (EN 100Cr6). Table 1 summarizes the chemical composition. The rings were submitted to a spheroidization heat treatment before machining to obtain globular carbides in a ferritic matrix.

<table>
<thead>
<tr>
<th>Table 1. Analysed chemical composition of the steel grade AISI 52100 (wt. %)</th>
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<tr>
<td>Element</td>
</tr>
<tr>
<td>AISI 51200</td>
</tr>
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</table>

Rings have been machined with different parameters. This resulted in different properties of surface layers and different residual stress distributions. As a result a wide range of residual stress states from compressive to high tensile stresses was covered. High tensile residual stresses are generated by the main manufacturing parameters as feed rate and depth of cut. The circumferential distribution of stresses depends on the clamping system [3, 4]. The machining sequence for all the rings was the same: the inner surface was machined first while the outer surface was clamped, then the clamping of the outer surface was released and the inner surface clamped for machining of the outer surface.

Basically a constant cutting speed of 240 m/min has been used for all rings. The depth of cut was kept constant at 0.75 mm and the feed rate on the inner surface was always 0.4 mm/turn. Varying parameters were the clamping system and the feed rate of the outer surface as given in Table 2.

<table>
<thead>
<tr>
<th>Table 2. Parameters used for machining of the investigated parts</th>
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<tr>
<td>Parts</td>
</tr>
<tr>
<td>752</td>
</tr>
<tr>
<td>909</td>
</tr>
<tr>
<td>933</td>
</tr>
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Pictures of the used clamping systems are given in Fig. 1
Fig. 1: View of the clamping systems used for the machining of the rings: a) pendulum chucks; b) expanding mandrel; c) three jaw chucks; d) chuck segment jaws

X-ray diffraction residual stress measurements of the outer circumference have been made with Bragg-Brentano diffractometers (type F, Siemens AG, Germany) equipped with scintillation counters. The computer controlled equipment enabled the automatic measurement of the whole circumference. Measurements on the inner face were performed on a Theta/Theta Bragg-Brentano Diffractometer (type Eta 3003 XRD, Seifert, Germany) equipped with a position sensitive detector and an active measuring area of 10° in 2Theta. Analysis of results was executed according to the standard sin²\(\chi\) method with following elastic constants: Young Modulus: 210 000 MPa, Poisson’s ratio: 0.28 [10]. The main measurement parameters are listed in Table 3.

Table 3. Parameters for the measurement of residual stresses by X-ray diffraction

<table>
<thead>
<tr>
<th>Position</th>
<th>Radiation / Filter</th>
<th>Detector</th>
<th>Prim. beam</th>
<th>Lattice plane</th>
<th>Tube voltage / current</th>
<th>Chi Angles</th>
<th>Step</th>
<th>Time/step</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outer face</td>
<td>Cr-K(\alpha)</td>
<td>Scintillation. Counter</td>
<td>Ø 2.4 mm</td>
<td>(\alpha{211})</td>
<td>35kV / 35mA</td>
<td>11 angles from -45° to +45°</td>
<td>0.05°</td>
<td>3 s</td>
</tr>
<tr>
<td>Inner face</td>
<td>Vanadium</td>
<td>PSD</td>
<td>Ø 2 mm</td>
<td></td>
<td>40kV / 40mA</td>
<td>10°</td>
<td>54 s</td>
<td></td>
</tr>
</tbody>
</table>

In order to have an almost complete surface characterization, residual stress measurements for cylindrical rings have been made on 36 points in the middle height around the external periphery (every 10°). X-ray diffraction measurements on the internal surface of the rings were not possible without cutting the rings. The rings have therefore been cut and measured at
10 positions in the middle height. Prior to cutting, those were measured with the micromagnetic method as explained in the following paragraph. Figure 2 gives sketches of the rings and measurement positions on the outer and inner surface.

![Sketches of the ring and positions measured by X-ray diffraction](image)

**Fig. 2** Sketches of the ring and positions measured by X-ray diffraction

Measurements of residual stresses by the micromagnetic method have been performed with a Qualimax system (Manufacturer: Stiefelmayer, Saarbrücken, Germany). This equipment records 19 electromagnetic parameters at the same time based on four different testing principles. These are: multifrequency eddy current, upper harmonics of the tangential magnetic field, incremental permeability and Barkhausen noise. The sensor contains a brace coil for the primary magnetization with 30 mm in length and 11 mm in width, a sensor (8 × 8 mm) for the acquisition of the parameters and a Hall-effect probe for the control and the measurement of the magnetic field.

All settings of the equipment have been kept constant. The standard excitation was 200 Hz and 50 A/cm. For the Eddy Current analysis, 3 frequencies have been used: 100 kHz, 200 kHz and 500 kHz. For the measurement of the incremental permeability, a frequency inloop of 100 kHz has been set. Finally, the Barkhausen Noise analysis used a Bandpass filter with cutting frequencies of 200 kHz (lower limit) and 6 MHz (upper limit).

The calibration strategy used X-ray diffraction data from 10 consecutive positions of each single ring. This resulted in a specific calibration for each investigated component. A general calibration for all rings has also been tested.

After calibration, the components were completely characterized with a mean value of ten measurements for each point. For all rings this measurement sequence has been repeated 3 times and a final mean value was calculated. So far each data point is the mean of 30 individual measurements. The measurement positions on the outer surface were the same than those given in Fig. 2. At the internal face, one circle at middle height with 36 points (every 10°) has been measured.

The measurements on the internal face of the rings were more difficult since it was not possible to measure residual stresses by X-ray diffraction without cutting the rings. Consequently, the rings have been measured first with the micromagnetic apparatus and an assumed calibration and then cut for measurement at ten positions by X-ray diffraction (figure...
As only machining residual stresses are expected to be present in the parts, the cutting should not affect the residual stress state at the measured positions because those were at sufficient distance from the cut. Afterwards, a back-calibration with micromagnetic data has been done by the measured X-ray data of the inner face of the ring and the residual stresses were recalculated.

RESULTS AND DISCUSSION

For the micromagnetic measurement of residual stresses a polynomial given in Eq. [1] is used. This equation was established by the manufacturer of the equipment from a multiparameter statistical analysis of micromagnetic data of ground surfaces.

\[
RS = a_1 + a_2 \times \text{Im}_3 + a_3 \times \text{Im}_3^2 + a_4 \times \text{Phas}_3^2 + a_5 \times \frac{1}{K} + a_6 \times \text{IHcu} + a_7 \times \text{Iampl}^2 + a_8 \times \frac{1}{\text{Iampl}} + a_9 \times \frac{1}{\text{IHcu}} + a_{10} \times \text{Bampl}^2 + a_{11} \times \frac{1}{\text{Bampl}} + a_{12} \times (\text{Bampl} \times \text{BHcu}) + a_{13} \times \text{BHcu}^2
\]

where “Im$_3$” is the imaginary part of the impedance measured with the highest frequency during the eddy current test, “Phas$_3$” is the phase angle of the third harmonic, K is the total harmonic distortion of the tangential magnetic field, IHcu is the coercive field strength measured during incremental permeability test, Iampl is the maximal amplitude of the measured permeability, Bampl is the amplitude of the Barkhausen noise and BHcu is the coercive field strength measured during the Barkhausen noise test. Only 7 of the 19 measured parameters are used. These seven parameters have been identified to be the most sensitive to residual stresses in grinding processes. The coefficients from $a_1$ to $a_{13}$ are determined by a multilinear regression analysis during the calibration procedure of the equipment. The results given by the micromagnetic method are compared with X-ray diffraction data as a reference.

Fig. 3 Surface residual stresses measured by X-ray diffraction and the micromagnetic method on the ring 752: a) outer circumference; b) inner face
Fig. 4 Surface residual stresses measured by X-ray diffraction and the micromagnetic method on the ring 909: a) outer circumference; b) inner face

Fig. 5 Surface residual stresses measured by X-ray diffraction and the micromagnetic method on the ring 933: a) outer circumference; b) inner face

Figures 3, 4 and 5 represent comparisons of tangential and axial residual stresses measured by X-ray diffraction and micromagnetic methods on the outer circumference and on the inner face of three rings. For the measurement of both residual stress components (axial and tangential) a rotation during X-ray diffraction measurements as well as of the sensor head of 90° was necessary. As known, the applied magnetization field interacts with residual stress fields in the same direction.

It can be seen that the periodicity of the residual stress distribution on the inner face is at least of third order or higher, so that at least one half period was measured by XRD. For all three rings results obtained by the micromagnetic measurements agree quite well with results given by XRD. Discrepancies are confined in a range lower than 50 MPa in almost all cases. This corresponds to the standard deviation associated with both measurement techniques.
However, a significant source of error could be the difference between the penetration depth of the X-ray diffraction analysis (5 µm) [10] and the different penetration depths during the analysis of magnetic and micromagnetic materials properties (3 µm to several hundred µm) [12]. The penetration depth is correlated with the instruments settings and the testing principle (eddy current, upper harmonics of the tangential magnetic field, incremental permeability and Barkhausen noise).

Concerning the machining parameters, effects from the clamping system as well as from the feed rate can be evaluated. For all rings the tangential residual stress component (cutting direction) is always shifted to higher tensile stresses compared to the axial residual stress component.

As shown in Figure 3a and 5a (both rings were clamped with a pendulum and expanding mandrel), a distribution with a periodicity of order 6 on the outer surface can be noticed for tangential residual stresses. For these measurements, the standard deviation of the values is in the range of 10 MPa, so that one can affirm that this 6th order periodicity is not due to scattering effects but is actually present in the rings. The 6th order periodicity for both rings is not as easy to detect as the 3rd order periodicity for ring 909. However, with the help of Fourier analysis, the 6th order periodicity could be assessed. The distribution is related to the pendulum clamping system, as 6 localized clamping points along the outer circumference are used. The 6th order of periodicity can also be seen on the inner face of ring 752 (Figure 3b) for tangential and for axial residual stresses. The amplitude is not very pronounced. On the other hand, ring 933 (figure 5b) shows a very high amplitude of 6th order on the inner face for both tangential and axial residual stresses. The only difference between these two rings is the change of the feed rate used for the machining of the external surface. Its effect on the residual stresses can be seen on the level of stresses present at the surface of these two rings.

Indeed, ring 752 (figure 3a) which has been machined with a feed rate of 0,1 mm/turn presents a much lower residual stress state than ring 933 (figure 5a) which was machined with a 0,4 mm/turn feed (Table 3). The effect of the feed rate on the residual stress level agrees with results obtained in a prior study [4]. Concerning the amplitude of residual stresses on the inner surface, the differences between rings 752 and 933 could therefore result from the level of residual stresses on the outer surface. For confirmation of these effects, further investigations will be executed.

The effect of the three jaw chuck clamping system on the outer face can be seen in figure 4. In this case, a periodicity of order 3 can be noticed on the outer as well as on the inner residual stress distribution. Like for rings 752 and 933, only the tangential residual stress component presents this periodicity on the outer face while both tangential and axial residual stress components show it on the inner surface. The reason why in all cases the axial residual stress presents almost no periodicity on the outer face while the periodicity is present in axial direction on the inner face may come from the machining sequence.

CONCLUSIONS

Concerning the effect of the machining parameters the clamping system causes a periodicity of the residual stress distribution along the inner and outer circumference of the rings. There are some differences between the inner and outer axial residual stresses. The second point is that the feed rate has a strong effect on the average level of the residual stresses. Other interactions cannot be excluded concerning the periodicity of the residual stresses. Beside the residual stress states produced by machining, this study shows that the micromagnetic method
is able to give rather quick measurements of surface residual stress distributions for the outer circumference but also for their inner surfaces. However, a good calibration with X-ray diffraction data is required and was done separately for each component on the outer and inner surface and for tangential and axial residual stresses. This method has several advantages compared to X-ray diffraction, namely, rapid measurements (after calibration has been done) and the accessibility for measurements on the inner surface. A detrimental feature of this method is the need of a specific calibration for each materials state. If the microstructure of the steel batch is different, or if the manufacturing is slightly changed, a new calibration would be needed. Nevertheless, the procedure could be adapted for the control of large manufacturing series. After a calibration with one ring at the external and inner surface (by cutting the ring), all rings could be measured without being destructed.

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