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Investigation into wear mechanisms of the bearing raceway used in bucket wheel excavators

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ABSTRACT

This article presents the macro- and microstructural analysis of bearing raceways. Raceways of bearings, taken from two machines which had worked 100,000 and 30,000 h, were examined. This provided crucial information on the exploitation history of both bearings, which is especially important for the future design process. After these initial macroscopic observations, it was determined which areas of the bearing had been most severely worn. This was indicated by the areas in which the chassis stiffness was highest. Further microscopic analysis of the individual bearing sections was useful for the identification of the dominating, destructive mechanisms in these areas.

1. Introduction

The main problem with the basic machines, used for open mining, is the construction of the rotational connection between the upper and lower structure. This must be constructed in such a way that it is possible to transfer large axial and radial forces and significant overturning moments. One of the basic movements of these machines is the rotation of the superstructure around the vertical axis. The joint for structural rotation, used in the surface mining machines, is usually constructed as a double shell element connected with the large sized bearing. A significant problem, which occurs only in this type of machine, is deformation wear of the raceway during the initial operation period. The high intensity of rolling, during the initial rotational movements of the upper body, alters the raceway geometry. For this reason, it becomes crucial to forecast the growth of plastic deformation and to determine the maximum loads that occur until the deformation and wearing become stable. The large sized bearings are constructed differently to the conventional bearings used in working machines. These differences include: much larger dimensions; a large number of rolling elements (up to several hundred in the largest bearings); slower running; the material used (meaning that an individually prepared heat treatment process according to this material must also be carried out); a small range of rotational movement of the upper body relative to the chassis during the whole working cycle; complexity of the external load transmitted through the bearing; difficulty in determining their exact kind and value; and the individual

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working conditions of machines in which the large bearings have been used.

The large sized rolling element bearings, used for turning the upper body of machines working in open-pit mining, are made in the form of single- or double-row ball bearings. As shown in [1], the bearing section diameter may be up to 20 m and the rolling element diameter ranges from 100 to 250 mm. These are both put under eccentric axial loads which range from a few to tens of MN. The load exerted on the rolling elements is uneven due to the supportive element's low stiffness and its non-uniform distribution around the bearing circumference. The load stream flow concentrates at points within areas of high stiffness. The bearing raceways are made of structural steels, which are usually normalized or occasionally thermally toughened. At present no quenched surface raceways are used. This is due to the technological difficulties of creating an adequate layer of hardened surface and the rapid process of damage to the surface, since the first hardened part of the surface is separated. In [2], the formula for the approximation of the rate of deformation wear in large-size bearings is described. This is given as a function of the ball diameter; number of load cycles; and two constants, which depend on rolling element specific load.

2. State of the art

Large-size bearings work until destruction of the raceway reaches the limiting value. This failure initially occurs as deformation wears and as the material being subjected to plastic flow extending over the raceway surface. In the final stage it occurs as fatigue breakout and crumbled out material.

Fig. 1 shows wear mechanisms in rolling-element bearings. Durability of high-loaded bearings with monolithic raceways is usually limited by loss of the basic geometric parameters.

During the use of monolithic soft bearings, stages of wear development can be distinguished. The first being the stage of intensive initial rolling, 'initial' being defined as occurring during the first few hundred to thousand hours of work. This phase is affected by the machine load and plastic behaviour of the raceway material. The second stage is the stable increase of deformation wear. This is material movement, mainly in the transverse direction, due to plastic flow. The third stage is the peeling formation due to pitting and fretting. In this stage separated material is transported in the lengthwise direction and rolls repeatedly. The initial phase of this stage depends on fatigue changes in the raceway material.

Deformation wear occurs through the flow of the raceway material and rut formation alters the local radius of curvature. Warping of the raceway surface is observed, this is where the value of the raceway radius approaches that of the ball's radius. Pitting in the bearing consists of the rolling element or raceway surface layer of material becoming destabilized. Pitting occurs at the lubricated abutment while rolling (with or without skid). The destruction mechanism consists of the formation of micro and macro sub-surface cracks. These occur in the surrounding area of the most strenuous point. Additionally, surface cracks form at the point where tensile stresses occur due to material fatigue. Oil is pumped under high pressure, caused by rolling with or without skid movement, to these resulting discontinuities. The lubricant causes a further increase in the existing micro cracks and connects the neighbouring discontinuities, causing the material to break apart.

The configuration of large size bearings: raceway-rolling element-raceway has a significant stiffness (when compared to the components of the support) what causes uneven deformation of the raceway. This configuration has several positive attributes, including self-acting correction of the bearing and reduced forces acting on the rolling elements of hard zones. The roll out of the raceway eliminates the flatness imperfection of the bearing's rings).

A number of papers on numerical methods of durability analysis of large size bearings can be found in the literature. Kunc and Prebil [3], compared three computational methods to determine the fatigue lifetime of bearings: stress-life, strain-life and the ISO standardized calculation approach. They showed that the choice of method has significant effects on the fatigue lifetime results. Moreover, the experimental characterization of the material should be taken to ensure accurate results. In the paper [4], authors presented an application of finite element analysis for identification of the load distribution on the bearing's rolling elements. This took into account the phenomena occurring in the raceway-rolling element-raceway assembly; rigidity of the support elements; and mounting bolts. The authors compared the

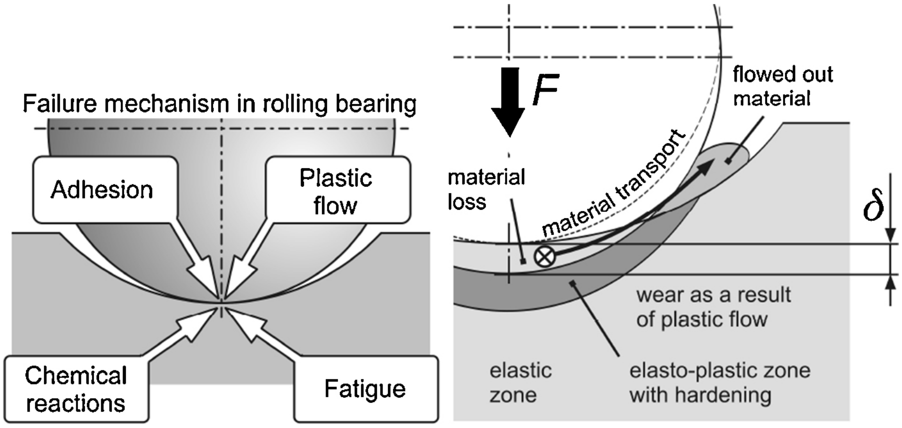

Fig. 1 – Mechanisms of wear in rolling-element bearings.

results with the classical model (an iterative solution), not taking the deformation of the support elements under load into account. A significant difference in the load distribution as well as in the maximum load values was observed. All numerical simulations for estimating the durability of large size bearings should be preceded by the analysis of the bearing raceway's material, during and after the operation. However, such studies are difficult to carry out due to the continuous work of machines in open-pit mining and demolition of the bearings only occurs in the case of their failure. There are very few publications which present the results of this type of study.

The purpose of the article is to analyze the macro and microstructure of a large size bearing raceway material. Firstly, the bearings were disassembled and the dislocation wear of the raceway surfaces measured. This allowed comparison of the deformation wear of each bearing, as well as determination of the deformation wear distribution over the bearing circumference. The lower raceway of the bearing in particular, which had worked 100,000 h, was thoroughly analyzed. Casts were made of this raceway and the relative curve angles were measured. Next, macroscopic research was carried out to observe different wear mechanisms and their intensity over the circumference of the bearing. Several studies of the material microstructure were conducted in order to obtain detailed observations of changes in the material.

3. Experimental details

The subject of this research have been the ball bearings used in turning the upper body of the A2RsB 5000 stacker, as shown in Fig. 2, manufactured in the former German Democratic Republic. These machines are used in lignite strip mines in Turow and Konin. The weight of both machine's upper bodies is about 640 tonnes.

This particular bearing, as shown in Fig. 3, has a section diameter of 10 m and contains 100 balls of 120 mm diameter. The bearing raceway is made of normalized steel. The raceways of two machines, used in two different mines, have been measured. They had worked 100,000 and 30,000 h, respectively, which roughly corresponds to 18 and 5 years respectively. Measurements for bearing after 30,000 work hours were taken during demolition of the second machine. For this reason, measurements were taken only for the lower raceway and in the smaller segment of the circumference

The dislocation wear of the raceway surface into the ring, in the disassembled bearings, has been measured as ≏g. The measurement was taken using an ultrasonic thickness gauge and verified at select points using a dial indicator. Deformation wear, as shown in Fig. 4, was measured in such a way that for the lower raceway it ranged from 5.2 to 10 mm and for the upper raceway from 2 to 16 mm. Based on many years of experience

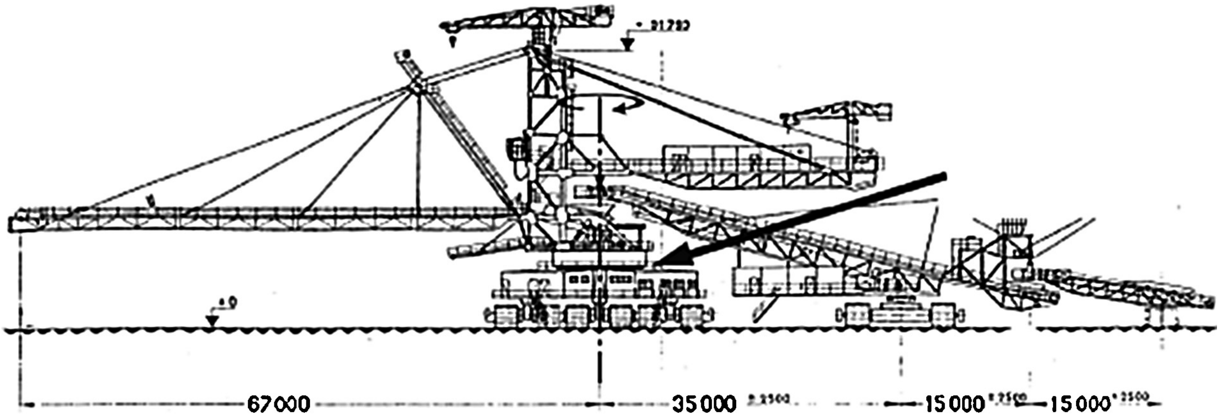

Fig. 2 – A2RsB 5000 stacker – general view, the arrow indicates the bearing which turns the upper body.

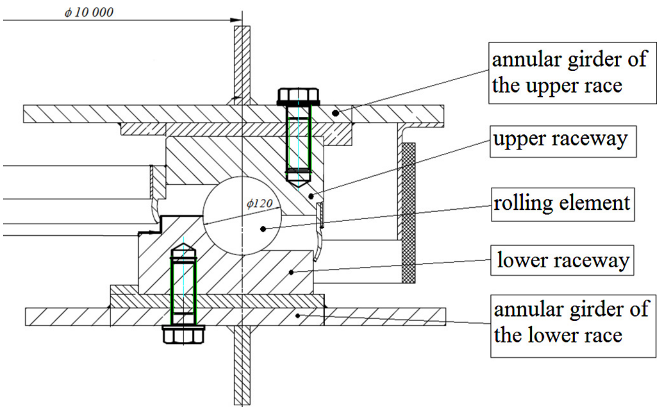

Fig. 3 – Upper body turning bearing-cross section.

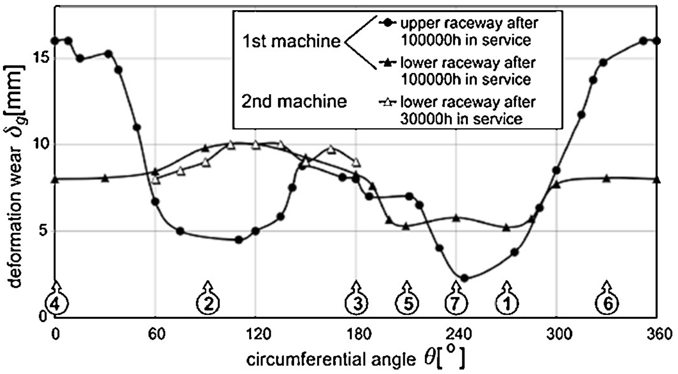

Fig. 4 – Deformations wear of the raceways of the stacker's bearing – a similar level of wear of the lower raceway in both machines, despite different service times. Arrows indicate sites of the raceway surface casts.

and conducting numerical simulations, Smolnicki [1] revealed that the distribution of deformation wear is highly correlated with disposition of stiffness over the circumference of the bearing. He also observed that the deformation wear was greatest in regions of highest stiffness within the load-bearing construction. Based on the results, it can be stated that deformation wear after 100 and 30 thousand of service hours is similar, which means the incidence of intensive rolling of raceway in the first stage of usage, after which time the phenomenon stops. After the initial deformation wears, further wear is very slow. In the first wear stage, the bearing has to adapt to load construction. It corresponds well with the experimental research on 42CrMo4 (40HM) and C45 (45) steels made by I. Prebil [5] and numerical simulations made by M. Stanco [6].

Casts, which display the raceway surface in 7 chosen sections on the bearing circumference, were made for the lower raceway and scanned with rapid prototyping technology. The cast material was a plaster based mixture. Select locations, for making casts, characterized the highest and the lowest wear. Rapid prototyping was used to collect points from the raceway surface. More details about this method are presented in [7]. The casts also enabled the measurement of average curve angles, as shown in Fig. 5. A detailed description of the measurement method was presented in [1,9].

The contact angles of the rolling elements are not constant but depend on the ball position relative to the upper and lower raceway. Mutual raceway displacements depend on the flexural stiffness of the support component in the radial direction. A considerable difference in curve angles between those sections were observed, as well as in the single sections themselves. In sections 1, 5 and 7, the existing rows have been marked with arrows. These are sections which show the least deformation wear (the least deep caving of the raceway). In section 2, which shows the highest angles, one can observe the largest deformation wear. In section 3, the raceway was rolled to a smaller extent. Measurements presented in Fig. 5 were conducted for the lower raceway of the bearing, which worked 100,000 h.

Referring to Figs. 3 and 4, large deformation wear of the raceway (which reaches, on average, 7% of the diameter of a

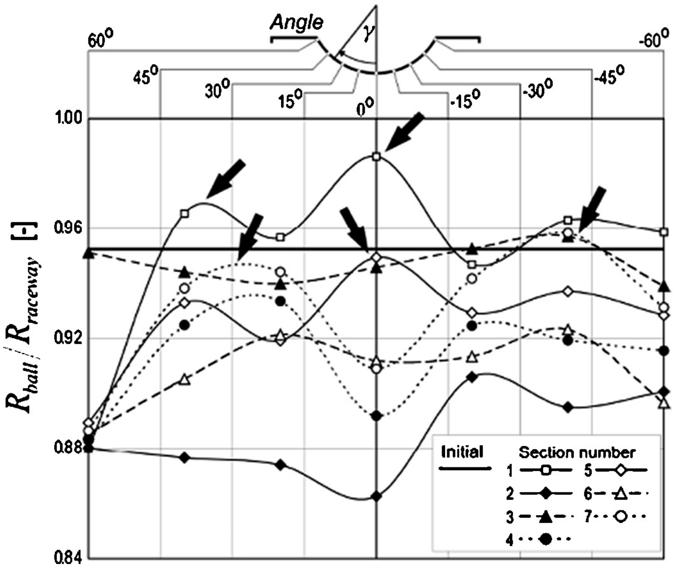

Fig. 5 – The relative curve angles in 7 selected transverse sections, along the circumference of the bearing. In sections 1, 5 and 7, the existing rows have been marked with arrows.

rolling element and at its peak 13% of this diameter) causes crucial alteration to the structure and parameters of the outer layer of the bearing rings. For this reason, the material strength and geometry change. Next, changes in the structure due to the degradation process can be observed. In order to identify these changes, a sample of material (taken from a bearing which was in service for 5 years) was examined.

4. Chemical composition analysis

The chemical composition of the material in ball bearing no. 1 was analyzed using the gravimetric and spectral method, with the results presented in Table 1:

The above chemical composition is typical for thermally altered steel of the kind '50H', as stated in the PN/H-84030/04:1989 standard. As the microscope examination has shown, Fig. 6, this steel has a fine, pearlite structure with ferrite grains and single small separated carbides. This structural state indicates that the steel used for the raceway was 50H in its normalized state (the so called soft state).

After normalizing and annealing, this steel should approximately show: Rm = 630 MPa and HB = 185 MPa. The measurement of material hardness, taken far from any deformation changes which are observable on a macroscopic scale, has shown that the average hardness equals 253 HBW. This difference in the hardness levels between an expected (185 HB) and measured (253 HBW) value is due to high pressure during exploitation and the following strengthening of the material.

The areas of the sample material, taken for further microscopic examination, are shown in Fig. 7.

5. Structure of raceway no. 1 material on a macroscopic and microscopic scale

Further macro- and microscopic research was carried out for the lower raceway of machine 1 (100,000 service hours). The upper raceway of this bearing was suitable for further exploitation.

In Figs. 8 and 9, the macroscopic views of sections of the ball raceway (after being etched with 3% solution of HNO_3) are shown. For the majority of the section, a homogenous macrostructure with some dendrite structure is observed. Additionally, in the region of raceway surface and ball interaction, there is a layer about 5 mm thick of darker colour than the rest of the surface. In this layer, one can observe macroscopic effects of the bearing being in service for 18 years, as on the left-hand side there is material flow out due to plastic deformation (Fig. 9a) with dimensions of 2.0 mm × 3.3 mm and a lack of continuity near the outer surface of the raceway. From the other side, as shown in Fig. 9b, the material is subjected to plastic flow shown by the trapezoidal shape extending over the raceway surface. On the semi-circular outline of the raceway, there are several pittings visible.

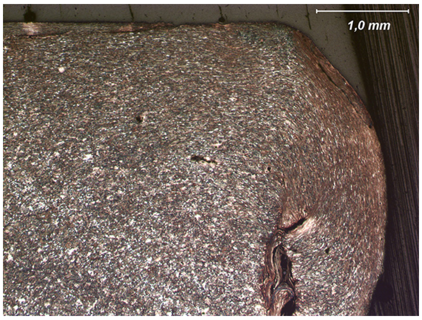

Fig. 6 – A microscopic image of the structural alterations and damages. Elongated visible (light) parts are ferrite separations. Magn. 25×, etched 3% HNO_3, light microscopy.

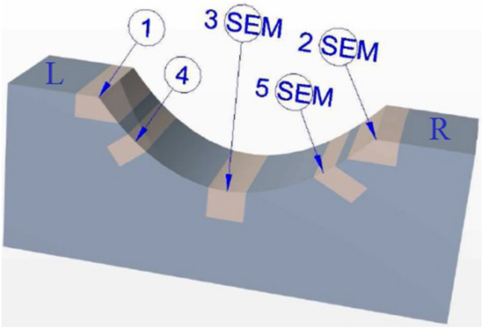

Fig. 7 – Areas of the sample material taken for further microscopic examination.

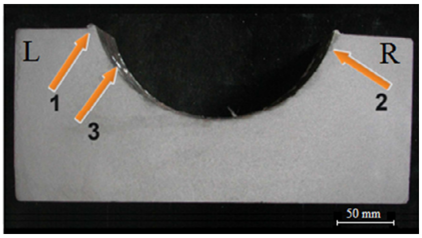

Fig. 8 – Macroscopic view of the transverse section of the ball raceway, homogenous surface of the section with not clearly visible traces of a dendrite type structure. L = Left side of the bearing, R = Right side of the bearing. 1: Left material flow out; 2: Right material flow out due to plastic deformation; 3: Ball-raceway interaction area. Etched with 3% HNO_3 (Mi1Fe), light microscopy.

Table 1 – Chemical composition of the bearing material.

C	Mn	Si	P	S	Cr	Ni	Cu	Mo	V
0.51%	0.67%	0.35%	0.05%	0.01%	1.04%	0.10%	0.15%	–	–

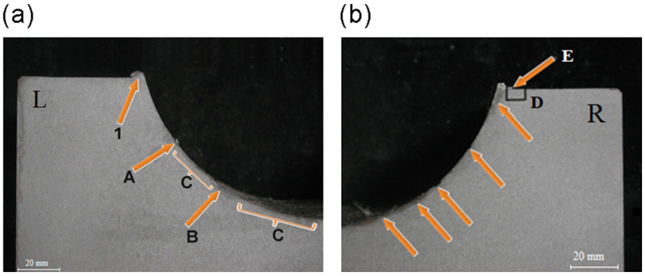

Fig. 9 – Macroscopic surface of raceway, view shown in Fig. 8: (a) Left side (L), in addition to the flow out, there are peelings visible on the surface of the ball-raceway interaction area (A), developed grid of macrofractures in under-surface area (B) and locally visible area of under-surface changes in the macrostructure (C), (b) right side (R), right flow out material with different shape than left flow out, different pitting visible in the location of ball- raceway interaction surface (marked with arrows). Etched 3% HNO_3 (Mi1Fe) light microscopy.

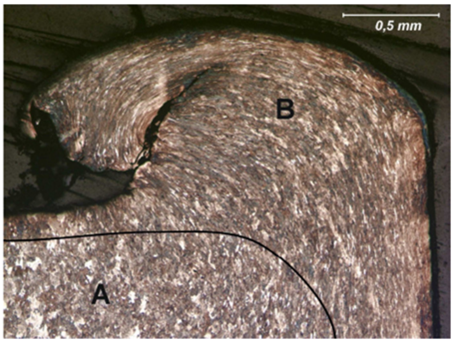

Fig. 10 – Microscopic image of structure alterations and damages in the left side material flow out area, shown in Fig. 9b. (A) Area of unchanged structure – pearlite with ferrite grains. (B) Structural area with different plastic deformations and plenty of structural incoherence. Elongated visible (light) parts are ferrite separations. Magn. 25×, etched 3% HNO_3, light microscopy.

Basing on the performed metallographic examination, one can postulate suggestions concerning the process of degradation of the examined ball raceway. The plastic transformation of the large size raceway has not caused total destruction of the post-cast dendrite structure. However, in the raceway section there is a macrostructure similar to a homogenous one. Microstructure of the material used consists of (out of the degradation areas) fine pearlite with ferrite.

It has been made out of 50H ''soft type'' steel (steel for heat treatment). This material has not been tempered, as it only underwent normalization annealing (according to the technical documentation and on the basis of the hardness measurements).

Macroscopic examination (performed on the transverse sections) has shown that, beneath the surface, there are areas which were of a darker colour than the rest of the bearing. In those areas (as shown in Fig. 9 – marked with arrows) much crumbled out raceway material has been observed. Another sign of degradation is the material flow out, which is present at both sides of the raceway, as a result of its being rolled. Shapes and size of the flow outs indicate clearly that uneven loading of the surface is present during its interaction with the balls. Macroscopic observation indicates more exploitation load on the left side of the raceway than on the right side. The right side is also characterized as being more homogenous and as having a smoother surface than can be observed on the left side. Increased wear on the left side has been caused due to the machine being operated with the body and chassis being positioned so that the eccentric bearing load was mostly on this side. Fig. 10 shows an enlarged view of the left side material flow out structure.

One can observe there is the area of the material free of plastic deformation (area A) and area where besides the clearly visible press texture there are areas of lack material cohesion of the raceway as a result of its exploitation. This area is full of plastically deformed; elongated; segmented; and separated by voids, fragments of raceway material.

An additional and crucial supplement to the above mentioned state of degradation is the state of raceway surface, as shown in Fig. 11. It indicates the pitting and fretting damage initiation mechanism, as discussed in this work.

On the described surface, there are dominating areas with huge plastic deformation (rolling of the raceway) and rolled 'products of pitting' in the form of crumbled out material being pressed into the surface. The surface of the raceway has an extensive topography with faults, macro-fractures and lack of cohesion filled during the service with corrosion products. This condition of the raceway surface (besides being from the exploitation load) generates and makes possible the development of further damage in under-surface layers.

A more clear view of changes to the micro- and macrostructure is present in the central part of the ball-raceway interaction area, as shown in Fig. 12. The area of maximal damage is between 0.4 and 0.5 mm below the surface of the raceway. Its width is variable and ranges from 0.2 to 0.4 mm. This area is full of plastically deformed; elongated; segmented; and separated by voids, fragments of raceway material.

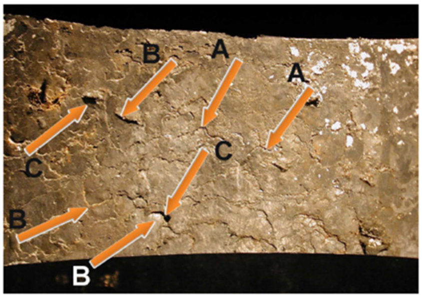

Fig. 11 – Macroscopic view of the area of the raceway with ball-raceway interaction after its service state. Developed topography of the interaction surface with plenty of fractures (A), faults (B) and pittings (C). Evidence of plastic deformation visible on the whole surface, not etched, light microscopy.

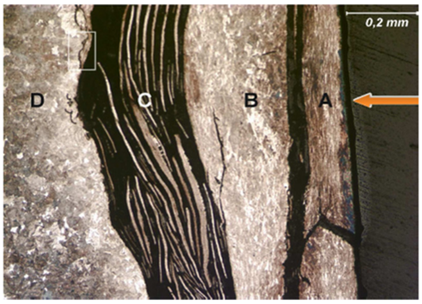

Fig. 12 – Macro and micro fractures of the undersurface layer of the raceway. (A) Undersurface layer – with maximal plastic deformation. (B) Intermediate layer – with less plastic deformation than A. (C) Area of maximal damage to raceway material (Bielajew point). Arrow indicates the ball-raceway interaction area.

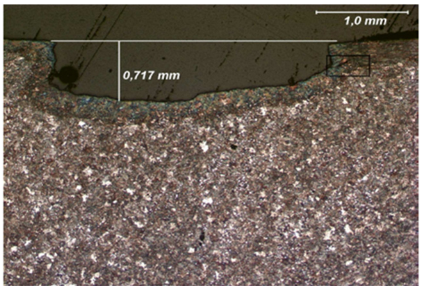

Fig. 13 – Extensive pittings all over the surface of ball-raceway interaction area.

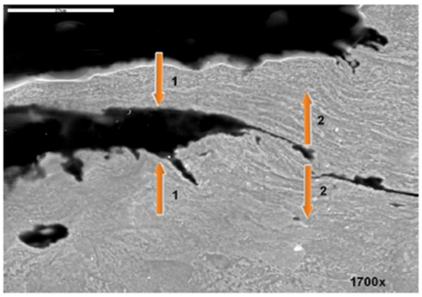

Fig. 14 – Enlarged image of the area marked with a box in Fig. 13. Ball pressure (1) opening of micro-fracture, (2) and lower propagation. Part (1) becomes segmented. Magn. 1700×, etched 3% HNO_3, SEM.

There are two more very characteristic areas, between this area and the surface of the raceway: area "A" with maximal plastic deformation containing macro-fractures and area "B" which is separated from the others and is less deformed and fractured. When measured from the recent surface of the raceway, the total deformation changes reach the value of 0.8 mm. It is to be expected that, during further service, the range of damage will develop further into the raceway. This is supported by micro-fractures coming from area "C". In intermediate areas between the bottom of the raceway and its outer layer, damages to the material is mostly in the form of crumbled out material (reaching roughly 0.7 mm).

The presence and development of micro-fractures (the white frame in Fig. 12), coming from the maximally damaged under-surface area (located deep in the raceway material), indicate that after some time in service and degradation of the under-surface layers of the structure, the maximum tension appears even in area "D". The shape and process of segmentation, separation from 'native material', indicates the presence of new Bielajew points located deeper (new I max, the point with greatest material stress) than the original location.

In the raceway 'bottom' region, microscopic images of damage seem to prove the thesis of maximum tensions being caused by bearing work located at some distance from the interaction surface (Bielajew point). The Bielajew point [10], is the area of the greatest stress of a material. This is located under the surface in the contact area of the raceway and rolling element and has been shown in Fig. 12 – area "C". This area shows, in segmented and separated fragments of the material, maximum deformation with characteristic micro-fractures present. These go only into the material of the raceway. Area "A", indicated in this figure, will undergo similar crumbling out (as shown in Fig. 13).

In the regions of accumulated tension, within areas of macro-fractures, there is initiation and development of further micro-fractures (as shown in Fig. 14). They develop mainly because of service load. The pressure generated by the ball on the area of the material (marked in Fig. 14 as 1) causes tension to spread to the area marked as 2, i.e. in the final part of the micro-fracture.

Data provided in this report, such as the results of the raceway 1 examination and the deep study into the characteristics of low-alloy martensites [e.g. 1 and 2], is brought together in the following conclusion. The main condition for increased durability of the raceway is the need for homogeneity of its material structure. In the case of 'soft raceways' it is the structure of pearlite with some traces of ferrite. A consistent, fine-grained structure is more resistant to fatigue and therefore, the aim is to extend stage 2 and delay stage 3 of wear. In the case of the raceway which underwent heat treatment, it has been shown that its service use is limited by the thickness of a layer with a tempered sorbite structure. This is because the whole section of the raceway has never been thoroughly tempered. In the case of surface tempering, the service hours of the raceway could be limited by the thickness of the martensitic structure layer. Material variants, in which heat treatment or surface tempering are used, pose problems as far as machining is concerned (higher hardness than in the case of 'soft raceways') and, especially after surface tempering, there is the possibility of increased inner tension. The optimum thickness of the hardened layer, in the case of rolling elements with a diameter of 120 mm, is about 5 mm. This is three times the depth of the Bielajew point. However, bearings with such pitch and rolling element diameters will, in most cases, not be hardened. Typically, these are normalized or quenched to a small hardness. Only surface heat treatment is performed. In the work, there has also been the following information: ''At present the manufacturers are not willing to share the types of materials used for ball bearings''. This indicates that new material solutions are being researched and used. It seems plausible to consider using the Hardox 350 steel for the lower part of the raceway and the Hardox 400 for the upper one; however more tests need to be carried out. In [10,11], authors presented the possibility of the use of a group of Hardox materials on selected elements of surface mining machines, exposed to abrasive wear. These are both low-alloy steels with martensitic structure and homogenous along the whole section. They have high abrasion resistance and very good load changing transmission. Their usefulness has been positively and experimentally verified using surface mining machines, in the case of bucket wheel chute panes and bucket wheel locks [12].

6. Conclusion

In conclusion, it has been shown that large size bearing do not wear evenly. The main form of wear is deformation wear, which causes changes to the depth of the raceway bottom and geometry (curvature). These geometric changes can reach up to 10% of the rolling ball's diameter. After the initial intensive phase of wear, the stabilization period follows. The final degradation stage is fatigue wear, which is characterized by severe pitting and micro-fracture of the material. Contrary to the conventional machine bearings, where durability is determined by the formation of initial damage, in low-speed bearings the rolling of pitting elements occurs and a secondary raceway is created. The study of the raceway's material showed that the most important step in increasing the durability of the bearing lies during the design stage. The key is to ensure a uniform stiffness distribution of the support components.

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