Investigation of impact of cutting oils on formation of surface defects during grinding

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Abstract. The paper proposes a new approach of evaluating the quality of cutting oils through the study of defects emerging on raceway surfaces of instrument bearings during profile grinding with use of different cutting oils. It has been also established that the wear of rubbing surfaces of bearings exposed to sliding friction generally depends on presence of defects and relates to fatigue fracture of the surface layer caused by repetitive thermomechanical exposures. Moreover, the wear rate depends on sizes and shapes of defects which act as stress raisers and so are of primary importance. Many experiments described in literature confirm that noise and vibrations directly depend on presence of defects on working surfaces of rolling bearings.

1. Introduction
The influence of cutting oil grade on the effectiveness of the grinding process and the quality of the raceway surface have been studied. The defects on the bearing raceways surfaces were investigated by means of optoelectronic equipment through calculation of arguments for the autocorrelation function obtained as a result of computer processing of the surface image.

2. Problem statement. Improving the technology of profile grinding of bearings with use of water-based cutting oils through the development of an optoelectronic data/measuring system for control of raceway defects.

3. Method of solution. The reviewed method allows detecting surface defects on the instrument bearings raceways that emerge during profile grinding with use of different cutting oils. The ground surfaces were analyzed with use of information technologies, the theory of measurement and digital image processing, the theory of correlation analysis, the probability theory, and mathematical statistics. The optoelectronic method applied is based on computer processing of raceways surface image using a quasi-optimal correlation algorithm.

4. Results of experimental studies. The process of profile grinding of instrument bearings raceways detailed in [1] has been carried out by means of a Bryant M-1 machine with fixed supports adjusted as follows: the angle between the supports was taken as $\beta = 105^\circ$, the angle between the adjustable support and the horizontal axis of ring $\alpha$ was taken as $7^\circ$ (according to theoretical studies, the optimal angle $\alpha = 5$–$10^\circ$), the coordinates of displacement of the rotation center of the ring relative to the rotation center of the faceplate were taken as $\Delta x = 0.2$ mm, $\Delta y = 0.3$ mm.

The grinding wheel 1–355x16x127 91A F320 M 9 V2 was used as a tool; the wheel has been dressed from time to time during the grinding process. The experience has shown that the wheel
dressing period amounts to 20–30 parts. The grinding wheel wear limit is 280x16x127. The wheel was dressed using of a Ts2 diamond dresser under the following conditions: \( V_w = 25.6–34.4 \text{ m/s} \), \( S_{\text{pop}} = 0.2 \text{ mm/stroke} \), \( S_{\text{fin}} = 15 \text{ mm/min} \). Cutting oil was continuously supplied to the working area during the process. Industrial oil (I-12 oil) and water-based cutting oil based on Avtokat F786 3% emulsion were used as cutting oils.

The grinding conditions varied within the following ranges:

The grinding speed was constant: \( V_w = 25.6–34.4 \text{ m/s} \); the peripheral speed of the part rotation was determined by the formula \( V_z = 60 \frac{V_w}{q} \), where \( q = 60–100 \). The process procedure requires \( V_z = 8.4–10.3 \text{ m/min} \), but this is significantly less than the calculated values; therefore, the rotation speed of the workpiece was increased up to \( V_z = 20.4–34 \text{ m/min} \) for the needs of the research.

The cross-feed rate varied within \( S_{\text{rough}} = 0.4–0.9 \text{ mm/min} \) during rough grinding and within \( S_{\text{finish}} = 0.2–0.4 \text{ mm/min} \) during finish grinding. The dwell period varied within \( T_m = 2–5 \text{ s} \).

The effectiveness of treatment of cutting oil to remove mechanical impurities was evaluated in accordance with GOST R 50558 with use of the following criteria:

- Residual concentration of mechanical impurities in cutting oil \( C_r, \text{ mg} / \ell \);
- The degree of purity \( \varepsilon \), allowing to estimate the relative removal of particles of mechanical impurities from the cutting oil: \( \varepsilon = 1 - \frac{C_r}{C_i} \);
- The average size of particles of mechanical impurities contained in cutting oil before treatment is \( d_i \), and after treatment is \( d_r \).

The results of the cutting oils quality analysis have shown the following:

1. The oil-based cutting oils contain as follows:
   - abrasive particles (whole grains which spall during the dressing, and fragments of grains);
   - metal microchips and lumps of them;
   - fragments of chips.

2. The concentration of particles of mechanical impurities at the inlet of the model unit for cutting oil treatment ranged 600–800 mg/dm³, which corresponds to a rather intensive grinding process.

3. The concentration of particles of mechanical impurities in purified cutting oil did not exceed 50–60 mg/dm³.

4. The degree of purification during the tests was found to be \( \varepsilon = 0.91–0.92 \).

5. The size (diameter) \( d_i \) of an average equivalent particle of mechanical impurities (before cutting oil treatment) settling with a rate of a real particle was 45–50 \( \mu \text{m} \).

Water-based cutting oil was based on ARS-21M emulsion: the solution included 3% of components and distilled water.

A model unit for water-based cutting oil precipitation-filtering treatment was designed. The model unit was a three-stage individual system for treatment of cutting oil with the flow rate of 7–8 l/min.

In the first two stages, thin-layer gravity purifiers were used with a gap between the precipitation plates equal to \( h = 5 \text{ mm} \). The velocity of cutting oil flow through the first treatment stage was \( V_1 = 0.006 \text{ m/s} \), and the section of working opening was \( S = 0.038 \text{ m}^2 \). The velocity of cutting oil flow through the second treatment stage was \( V_2 = 0.003 \text{ m/s} \), and the section of working opening was \( S = 0.075 \text{ m}^2 \). The unit capacity was \( Q = 13 \text{ l/min} \).

The velocity of cutting oil flow through the filter compartment was \( V_f = 0.021 \text{ m/s} \), and the effective cross section was \( S_f = 0.011 \text{ m}^2 \). The total filling volume of unit did not exceed 70 liters.

Operating principle of precipitation-filtering unit Large abrasive particles generally precipitated in the gap between the precipitation plates at the first stage (such particles are the first to precipitate out of the cutting oil). The parts of large metal impurities—aggregates and lumps—precipitated at the first stage as well. The metal particles are the continuous microchips and the individual fragments.

Sufficiently complete precipitation of lumps and individual microchips was ensured at the second stage due to twofold decrease in velocity of cutting oil flow through that stage; some of the individual microchips and their fragments, as well as thin fragments of abrasive grains (\( d_{\text{chips}} \leq 5 \mu \text{m} \)) passed through.
At the third stage, extraneous oils and products of decomposition of cutting oils in the cutting areas (the thermopyrolysis products) were released onto a sand surface. As a result, the quartz sand was accumulating a liquid oily product contaminated with mechanical impurities.

The specified design concept of treatment ensures the effective treatment of water-based cutting oil to remove large abrasive particles, microchips and lumps (“thread wastes”), as well as large fragments of microchips.

The efficiency of the treatment system was as high as \( \varepsilon = 96–98\% \), and the size of particles in purified cutting oil reduced down to 1–5 \( \mu \text{m} \).

The defects on the inner rings of instrument bearings which emerged during the grinding in production conditions were inspected using microscopes. The analysis of defects control procedures at Miniature Bearings Factory Ltd has shown that no significant results have been ever obtained through optical control methods with use of microscopes [2-3].

Within this study, the surface defects of raceways of bearing rings were investigated by means of optoelectronic equipment and the method developed. This method is based on comparative correlation processing of a halftone image of the raceway structure and a special set of halftone images of reference structures with known microrelief parameters. The paper proposes a way to identify the arguments for the autocorrelation function with center-line-average surface finish \( R_a \). It was proposed to use the average oscillation amplitude of the autocorrelation function \( A_{avrg} \) depending on level \( r (r = 0.61) \) and the sizes of reference window standards [4] as the altitude argument for the autocorrelation function.

The results of the autocorrelation analysis have shown that the surface defects change the raceway surface roughness \( R_a \) from 0.058–0.08 \( \mu \text{m} \) to 0.098–0.104 \( \mu \text{m} \); this cannot be determined by means of the other measurement methods.

The studies have revealed that the surface defects have emerged as a result of contact interactions between the working surface of abrasive tools and the surface of the workpiece, and also depend on the degree of cutting oil purification from grinding wastes. The surface defects were estimated in accordance with their relative importance which has been determined on the basis of their pairwise comparison and a certain set of features. The use of method of prioritization based on collective expert review was proposed [5-6].

The sequence of procedures in accordance with this method is as follows.

Let us assume that the bearing raceway surface has a defect \( X \) forming under the impact of factors \( Y \) which will be used for pairwise comparison of these objects.

The value of the relative importance (or the priority by the \( i \)-th attribute) of each object in the total amount is determined by the first level iteration method:

\[
K_i = \frac{Z_i}{\sum B_{ij}} \cdot 100 \%,
\]

(1)

where \( Z_i \) is the value of an object’s priority by a specific attribute, and \( B_{ij} \) is a coefficient analogous to representation of the \( i \)-th object’s superiority over the \( j \)-th object.

Each such element \( K_i \) means the relative number of priorities of this defect. The found \( K_i \) will be the parameters of defects.

Experimental studies have shown that the main factors affecting the formation of defects during the grinding are as follows: workpiece rotation speed, m/min [1]; coarse cross-feed rate, mm/min [2]; fine cross-feed rate, mm/min [3]; dwell period, s [4]; cross feed when dressing, mm/dbl stroke [5]; cutting oil grade [6]; cutting oil purity [7].

The surface defects emerging on bearing rings raceways were investigated by means of optoelectronic equipment [7-8]. Digital photos processing modes were as follows: 120 × 140 px frame format, base window with a standard size of 9 × 9 px, light source inclination angle 45°. Ten images have been shot along each ring raceway arc, and the ring was considered to be totally defective if defects have been detected at any image.

In total, there were investigated 500 rings which have undergone the profile grinding with use of oil-based and water-based cutting oils; due to this, typical defects have been identified. Figure 1 shows photos of ring defects which have emerged during the grinding with use of oil-based cutting oil.
Figure 1. Typical defects of the raceway during the profile grinding with use of oil-based cutting oil of grade I-12

Such a variety of defects emerging during the grinding with use of oil-based cutting oils is caused by the fact that after the grinding and the dressing, particles of abrasive grains as well as of sludge (chips) do not have enough time to precipitate in the precipitation tanks as the oil is highly viscous. That is why the number of defects on the working surfaces of raceways was up to 90%.

The studies have shown that grinding of rings with use of water-based cutting oils has reduced the number of defects down to 10 ... 15%. The shape and configuration of such defects are similar to those emerging during the grinding with use of oil-based cutting oil; however, they are shallower and emerge on a smaller number of rings (see Fig. 2).

Figure 2. Typical defects emerging on the raceway during the profile grinding with use of water-based cutting oil –Avtokat F786, a 3% emulsion

According to the results of the research, the following criteria of defects on the working surface of the raceway of the bearing ring have been identified (see Figures 1, 2): 1—grain fragments embedded in the surface; 2—influx; 3—discontinuities; 4—microcavities; 5—processed material (chips) sticking over the surface; 6—plowing; 7—formation of dimples; 8—spalling; 9—local destructions.

The depth of the defect was determined as the difference between amplitudes of autocorrelation function $A_{\text{avg}}$ for a surfaces obtained when a defect is present ($A_{\text{avg} \text{ i}}$) and when absent ($A_{\text{avg} \text{ j}}$), i.e. $\Delta A_{\text{avg}} = A_{\text{avg} \text{ i}} - A_{\text{avg} \text{ j}}$. The resulting value was inserted into the formula for calculating the scratch marks depth: $R_{zd} = 0.16 + 0.1 \times \Delta A_{\text{avg}}, \mu m$

For example, if grinding has formed the raceway surface defect which has affected the value of $A_{\text{avg} \text{ i}} = 14.0$, and the surface without defect had featured $A_{\text{avg} \text{ j}} = 13.4$, then the depth of the defect is $R_{zd} = 0.22 \mu m$, and the surface roughness is $Ra = 0.048 \mu m (R_{zd} = 0.192 \mu m)$ [2], i.e. the size of the defect $R_{zd} = 0.22 \mu m$ is comparable with the surface roughness height $R_{zd} = 0.192 \mu m$.

It can be seen from the Table 1 that the most significant defects are 1, 4, 8 and 9, and the dominating factors are 2, 5, 6, 7, i.e. cross-feed rate during the dressing of grinding wheel, coarse cross-feed rate during the grinding, type of cutting oil and quality of its clarification.
Table 1. Determining the value of relative importance $K_i$, %

| Defects | Factors | 1 | 2 | 3 | 4 | 5 | 6 | 7 | $K_i$, % |
|---------|---------|---|---|---|---|---|---|---|---------|
| 1       | +       | + | + | + | + | + | 4.9|
| 2       |         | + | + | + | + | + | 3.7|
| 3       |         |   | + | + | + | + | 2.5|
| 4       | +       | + | + | + | + | + | 6.2|
| 5       |         | + | + | 2.5|
| 6       |         | + | + | 3.7|
| 7       |         | + | + | 3.7|
| 8       | +       | + | + | 6.2|
| 9       | +       | + | + | 11.1|

As a result of research of surface defects emerging on raceways of the bearings inner rings during profile grinding with use of oil-based cutting oils, the following reasons for formation of such defects have been found out:

Reason 1. Traces (indentations) caused by the embedment of abrasive grain fragments into the working surface of the raceway emerge due to failure to comply with the established processing modes. In particular, they indicate a zero or insufficient dwell period.

Reason 2. Scratches emerge due to poor treatment of cutting oil. Abrasive particles brought to the cutting zone by the cutting oil are instantly caught between the surfaces of the wheel and the workpiece and so perform the cutting work until the grain fragment is crushed by the cutting forces and forms an indentation at the end of its movement.

Reason 3. Defects in form of chip clots show that the cutting oil is poorly magnetically separated.

Reason 4. Defects along the edges of the raceway surfaces emerge due to the impact of unbound abrasive particles containing into the cutting oil on the bearings raceway surfaces.

5. Conclusions

The use of optoelectronic equipment for investigation of defects on raceways of bearing rings has enabled the identification of defects and the determination of their sizes.

The method for analyzing the defects by their relative importance is proposed, and the reasons of their emerging are identified.

It is established that the main defects are formed as a result of poor treatment of oil-based cutting oils.

It has been proposed to apply water-based cutting oils to ensure smooth grinding of raceways of the bearings inner rings.

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