Non-destructive Prognostics for Rolling Bearings by Eddy Current Testing

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ABSTRACT

Rolling bearings, which are assembled into various industrial machinery, are regularly replaced after being used for a period of time, even if they have not failed. It is important to predict failure of rolling bearings not only for safe operation of machineries but also for resource conservation. The X-ray diffraction (XRD) is known as an effective method for estimating the remaining useful life (RUL) of rolling bearings. However, it is a destructive approach sometimes requiring cutting bearing rings. Therefore, non-destructive and simple diagnostic method for estimating RUL of rolling bearings using Eddy Current Testing (ECT) has been developed by focusing on the experimental evidence that changes in microstructure of the steel cause changes in the magnetic property. Rolling contact fatigue tests were conducted using several types of rolling bearings, and it was found that the ECT measurement results on raceway surface show a determined behavior with fatigue progress. The tendency of changes did not depend on bearing type, material or heat treatment. Additionally, measurement results by ECT were related to those by XRD. Above experimental results suggest that ECT can be applied to estimate RUL of rolling bearings as a non-destructive and simple method.

1. INTRODUCTION

Rolling bearings are important mechanical elements assembled into rotating systems of various industrial machineries. Failure of rolling bearings such as spalling due to rolling contact fatigue (RCF) causes machine downtime and could result in serious accidents at the worst case. For this reason, rolling bearings are typically replaced after a certain period of use, even if they have not failed. Enabling the utilization of bearings up to the point just prior to failure, by estimating when they may fail, can contribute not only to the safe operation of machinery but also to resource conservation. X-ray diffraction (XRD) is an effective method for estimating the remaining useful life (RUL) of rolling bearings. It was found that XRD could quantify the amount of change in microstructure of the bearing steel caused by RCF (Furumura, Shirota & Fujii, 1982, Oguma, 2002, Kamura, Fujita & Sasaki, 2018). Also, Vegter, Buslaps and Kadin (2015) proposed that residual stress could be measured by Synchrotron Radiation to quantify the RCF. However, these approaches are sometimes destructive depending on the shape or size of the bearing and not easily implemented at a manufacturing site.

From a resource conservation perspective, it is essential to have a non-destructive method for inspecting bearings that enables their reuse. For example, Kadin, Bertelli and Kirilyuk (2018) attempted to quantify fatigue progress by detecting changes in magnetic property of materials. Eddy Current Testing (ECT) is known as one of the non-destructive inspection methods to detect changes in magnetic properties (García-Martín, Gómez-Gil & Vázquez-Sánchez, 2011). Kanazawa, Hayakawa, Beltran, Yoshimoto, Saito, Maruyama, Uchiyama, and Sasaki (2021) found that changes in microstructure could be evaluated by ECT from roller-pitching tests. Bearing steels consist of two types of microstructures which are martensite and retained austenite with different crystal structures. When a rolling bearing is used, lattice strain in martensite gradually decreases over time, which may alter the behavior of magnetic domain wall motion. Moreover, the amount of retained austenite, a non-magnetic phase, also decreases. Therefore, the alterations in microstructure due to RCF may lead to changes in the magnetic properties of the bearing steel.

Based on the background describe above, a non-destructive and simple diagnostic method for estimating RUL of rolling bearings has been developed using ECT. The developed method can be performed quickly and easily even at the manufacturing site.

2. ECT TRIALS USING VARIOUS HEAT-TREATED SAMPLES

2.1. Principle of ECT

Figure 1 shows schematically the ECT principle. When alternating current, *I* is applied to the coil as a sensor, magnetic flux, Φ is generated in the direction perpendicular to the current, *I*. The coil is brought close to a conductive material, then an eddy current, *i* is generated on the material surface due to electromagnetic induction. The eddy current, *i* generates a magnetic flux, ϕ in the opposite direction. This magnetic flux, ϕ causes a change in coil impedance, *Z*. Here, when the eddy current, *i* changes, it affects the magnetic flux, ϕ, resulting in change of the coil impedance, *Z*. ECT is the method of detecting such change in the coil impedance as a voltage signal in the X-Y coordinates using a bridge circuit including the coil. Factors that affect the eddy current, *i* are surface defects and magnetic properties of the material such as magnetic permeability and electrical conductivity.

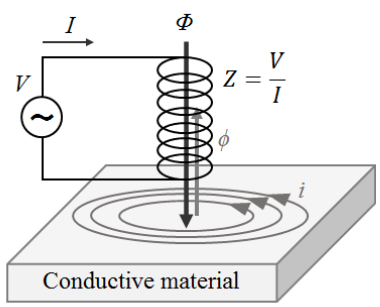


Figure 1. Schematic of ECT principle.

2.2. ECT results using various heat-treated samples

In order to verify whether differences in microstructure of the bearing steel can be detected by ECT, measurement trials were performed on disc-shaped samples obtained from bearing steel (JIS-SUJ2) using a commercially available ECT device. The samples were quenched from 800 to 880 °C and tempered from 140 to 240 °C. The sensor used for the measurements was a mutual-induction type and probe coil containing an iron core with a diameter of 3 mm. Excitation frequency was 128 kHz. ECT results were plotted on X-Y coordinates. Phase angle on ECT device was adjusted so that the change depending on gap between probe coil and sample surface (liftoff) appears on the X-axis.

Figure 2 shows ECT results. The measurement plots vary depending on the heat treatment condition and are on single straight line. Differences in heat treatment conditions cause changes in the lattice strain of martensite and the amount of retained austenite, which are similar to the microstructural changes due to RCF. These results indicate that changes in the microstructure of bearing steel can be evaluated as magnetic changes. These trials support the hypothesis that the progress of fatigue in rolling bearings can also be evaluated by ECT.

The repeatability of ECT was confirmed by conducting 30 measurements on the sample, which was quenched at 840 °C and tempered at 170 °C. The standard deviation, σ, for both X and Y voltages was found to be approximately 0.01 V, which is negligible in relation to the changes in ECT values due to microstructural changes.

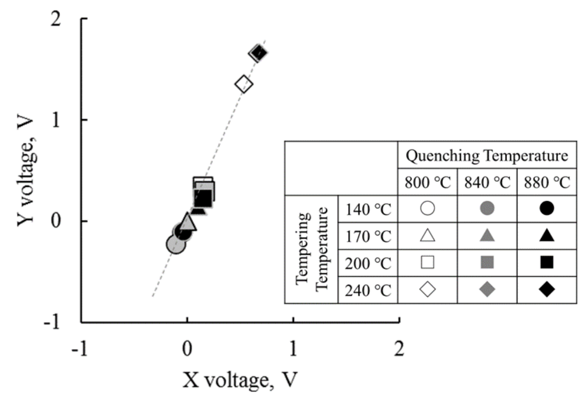


Figure 2. ECT results of various heat-treated samples.

3. EXPERIMENT

3.1. Experimental procedure

RCF tests were carried out using various types of rolling bearings, materials and heat treatments. Details of the tested bearings, heat treatments and RCF testing conditions are shown in Table 1, 2 and 3 respectively. RCF test rigs have a common configuration where the inner ring of the bearing is fixed to rotating shaft, and the outer ring is fixed to housing. The RCF tests using tapered roller bearings were conducted under contaminated lubrication in order to accelerate fatigue. Each test continued until spalling occurred or up to 1500 h. Some of the tests were interrupted after several periods of time. The test bearings were removed from test rigs and disassembled. XRD and ECT measurements were directly performed on the raceway surfaces of the outer rings for tapered roller bearings and on the inner rings for spherical roller bearings, where they had loaded areas. Subsequently, the bearings were reassembled to continue the RCF tests. These interrupted tests were restarted after both XRD and ECT measurements. In the experiment, XRD measurements where only on the surface, that why the test bearings could be reused. As for the test-completed bearings, the same measurements were performed at eight equipartition points in the circumferential direction of both inner and outer ring raceway surfaces. Cr K Alfa X-ray with collimator size of 2.0 mm was used for XRD. Full width at half maximum (FWHM) of martensite was measured from X-ray diffraction profile of α211. ECT measurements were conducted at same positions where XRD was performed under the same conditions described in Section 2.2 to compare with XRD results.

Table 1. Details of tested bearings.

Bearing	a	b
Bearing No.	32017	22211
Type	Tapered roller bearing	Spherical roller bearing
Outer dia.	130 mm	100 mm
Inner dia.	85 mm	55 mm
Dynamic load rating (C_r)	143 kN	149 kN

Table 2. Material and heat treatment condition.

HT condition	i	ii	iii
Material	SUJ2	SUJ2	SCr420
Quenching	Through hardening	Through hardening	Carburizing
Tempering temperature	240 °C	170 °C	180 °C

Table 3. Conditions of RCF tests.

Bearing No.	32017			22211
Bearing set	A	B	C	D
Tested Bearing.	a	a	a	b
HT condition	i	ii	iii	i
Radial load	61.5 kN			45.2 kN
Axial load	18.5 kN			-
Rotating speed	1500 min^{-1}			
Testing time	Within 1500 h			
Lubrication	ISO-VG68 (contaminated)			ISO-VG68
Calculated rating life (L_{10})	185 h			592 h

3.2. Fatigue progress evaluation using XRD

Quantifying fatigue progress is necessary to verify whether changes in microstructure due to RCF can be evaluated by ECT. Therefore, XRD measurements were conducted using test-interrupted bearings to investigate how the FWHM of martensite changes due to RCF. Figure 3 shows in the XRD measurements result of ΔFWHM over time, which is difference from the FWHM value before testing. Testing time, which is the horizontal axis in Figure 3, is shown in ratio to calculated rating life (L_{10}). It is evident that the ΔFWHM increases gradually, up to approximately 2.5 degrees, with testing time regardless of bearing type, material and heat treatment, indicating that ΔFWHM has correlation with the fatigue progress. In order to verify the effectiveness of ECT for predicting RUL of rolling bearings, ECT and XRD measurement results will be compared.

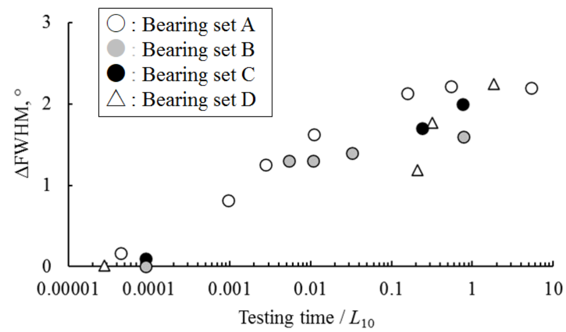


Figure 3. Change in ΔFWHM according to testing time.

3.3. Result and discussion

3.3.1. ECT results of different type bearings

ECT results using tapered roller bearings obtained from JIS-SUJ2 with through hardened and tempered at 240 °C (Bearing set A) are shown in Figure 4. The results are classified into four groups based on the ΔFWHM value ranges (Group I: less than 0.5 °, Group II: 0.5 ° or more and less than 1.5 °, Group III: 1.5 ° or more, Group IV: 1.5 ° or more with spalling). The results of the ECT are shown as relative values, with reference to the new bearing before testing. This indicates that the values of the new bearings are plotted around the origin. It is found that ECT values shift towards the third quadrant of the X-Y coordinates as the ΔFWHM increases for Groups I, II, and III. On the other hand, the values of Group IV, where spalling occurs on the raceway surface, exhibit a distinctly different tendency from the other results.

Figure 5 shows the ECT results using spherical roller bearings (Bearing set D). The results are also classified into four groups based on the ΔFWHM value ranges. It is clear that the ECT values shift towards the third quadrant of the X-Y coordinates as ΔFWHM increases for Groups I, II, and III, reflecting the same trend observed in the results of Bearing set A.

The results shown in Figures 4 and 5 indicate that the behavior of the change in ECT values due to RCF do not depend on the bearing type. The tendency observed in groups I, II, and III, which is shifted linearly to the third quadrant of the X-Y coordinate, is also observed in changes due to differences in heat treatment conditions, as shown in Figure

2. Therefore, this tendency is considered to be caused by the changes in the magnetic properties of bearing steel due to RCF.

The optical micrographs in Figure 6 show the raceway surfaces in Bearings set A at different stages of fatigue progression. Notably, Group IV, where spalling has occurred, displays a markedly different surface condition compared to Group II. It is worth mentioning that the surface condition has a significant impact on the ECT results. Thus, surface defects such as spalling, indentations, and fatigue cracks affect the ECT values in Group IV, rather than changes in the microstructure, resulting in a different tendency than the other three groups.

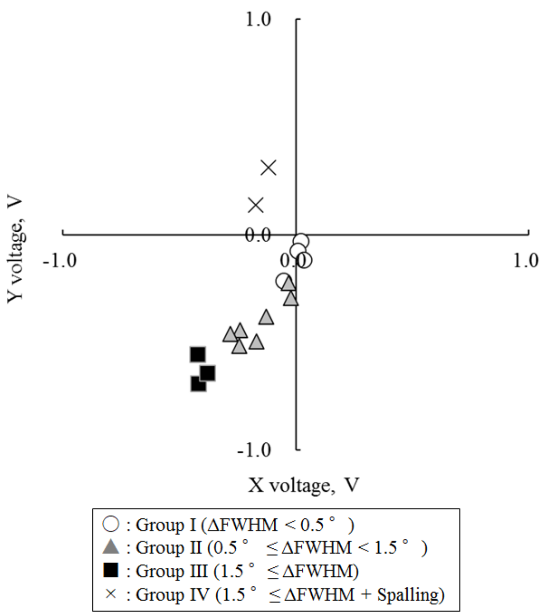


Figure 4. Change in ECT results of Bearing set A.

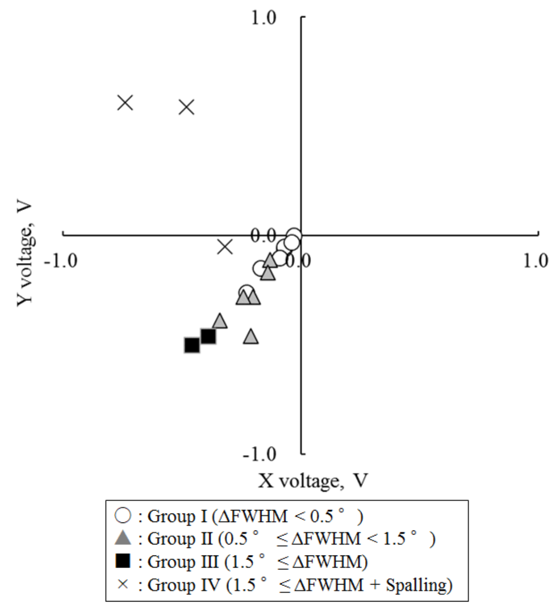
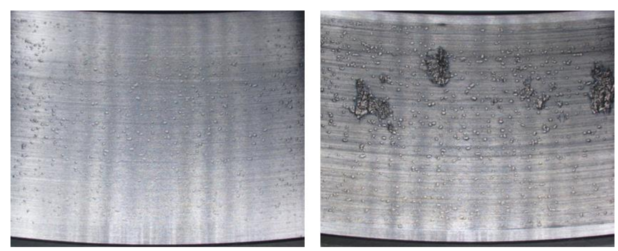


Figure 5. Change in ECT results of Bearing set D.



a) 0.5 ° ≤ ΔFWHM < 1.5 ° b) 1.5 ° ≤ ΔFWHM + Spalling

Figure 6. Optical micrographs of raceway surface in Bearing set A after RCF testing.

3.3.2. ECT results of bearings with different material and heat treatment

Figure 7 and 8 show the ECT results using the Bearing set B and C respectively, which are obtained from tapered roller bearings with different material and heat treatment from Bearing set A. It can be observed that the distance from the origin of the ECT values is less than that of Bearing set A and D. However, the ECT values exhibit a similar behavior, in that they shift to the third quadrant of the X-Y coordinates due to RCF progression. This tendency changes when spalling occurs, regardless of the material or heat treatment. These results suggest that tendency of changes in ECT values due to RCF is influenced by steel microstructure depending on the material and heat treatment.

The microstructure of bearing set B and C contains some retained austenite, whereas bearing set A and D have almost none due to a higher tempering temperature. Retained austenite is unstable phase and transformed to martensite induced deformation due to RCF. This martensite has much lattice strain, which may lead to changes that counteract RCF. For these reasons, it is presumed that the changes in ECT values of Bearing set B and C was less sensitive than those of Bearing set A and D.

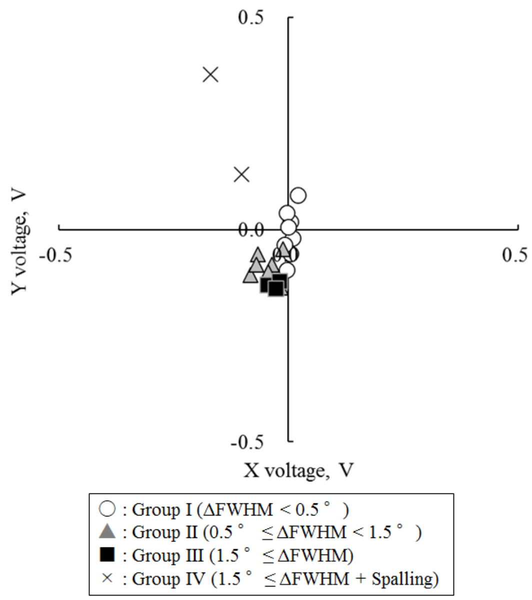


Figure 7. Change in ECT results of Bearing set B

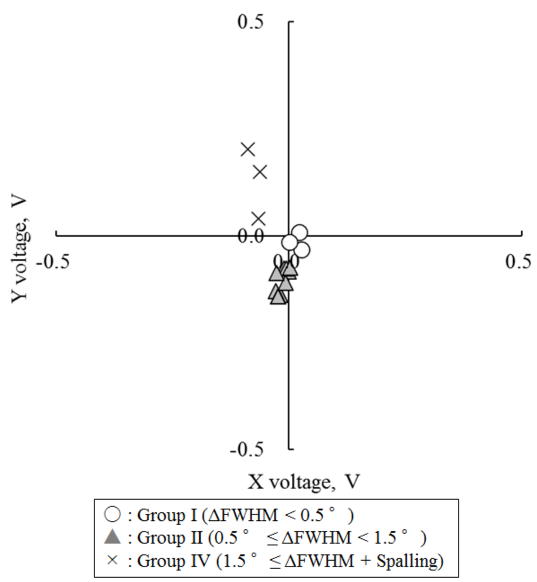


Figure 8. Change in ECT results of Bearing set C.

These results indicate that there is a correlation between ECT measurements and ΔFWHM regardless of bearing type, material or heat treatment.

It was demonstrated that fatigue progress and ΔFWHM are correlated (see figure 3). ΔFWHM can be evaluated by referencing Figures 4, 5, 7, and 8, thereby allowing the estimation of RUL.

4. Conclusion

Rolling contact fatigue (RCF) tests were carried out using various types of rolling bearings, materials and heat treatments to verify whether fatigue progress could be evaluated by Eddy Current Testing (ECT). Also, the results of ECT measurements were compared with those of X-ray measurements. The major findings are:

- Changes in ECT values have a determined behavior with fatigue progress, which does not depend on the bearing type, material and heat treatment.
- It is assumed that the tendency of ECT results is caused by changes in both microstructures of bearing steel due to RCF and the surface condition of the raceway.
- The changes in microstructure have a different effect on ECT values than changes in surface condition.
- The sensitivity of ECT measurements was influenced by material and heat treatment.

Based on the results described above, it is suggested that ECT could be a simple and non-destructive diagnosis method for predicting remaining useful life (RUL) of rolling bearings by understanding correlation between change in ECT value and fatigue progress for each material and heat treatment.

The diagnostic method by ECT requires the removal of rolling bearings from the machine system and disassembling them. Therefore, the application of this method is limited to mechanical systems with maintenance processes that involve disassembly and inspection of bearings. In addition, it should be combined with various diagnostic methods, such as dimensional shape analysis, surface condition evaluation, and vibration level monitoring during operation, to conduct a comprehensive diagnosis of RUL. However, these conventional diagnostic methods often rely on the engineer's intuition and experiences. The ECT measurement could be a method that provide quantitative criteria for determining RUL of bearings, without depending solely on the experience of engineers.

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