Development of Non-destructive Grinding Burn Detection Technology

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Nitric acid etching, which is the conventional method used in manufacturing plants to detect grinding burn, has a number of problems, described as follows: (1) detection level varies depending on the operator and the equipment used; (2) the tested pieces must be scrapped as it is a destructive inspection; and (3) outflow of defective products cannot be prevented perfectly as 100% inspection cannot be carried out. This study was performed to develop a non-destructive inspection system to detect grinding burn, which can be used to perform quantitative 100% inspection within a production line. For this inspection, an eddy current sensor is selected because of its short measurement time and low cost. In this paper, a new method that simultaneously measures eddy currents of two different frequencies is proposed. This method reduces the misdetection of grinding burn by eliminating the effect of variance in base material. Furthermore, a Grinding Burn Detection System has been prototyped, and it has been confirmed that quantitative inspection is indeed possible.

Key Words: *grinding burn, non-destructive inspection, eddy current, retained austenite, magnetic permeability*

1. Introduction

Grinding burn is one issue faced in the grinding process. Broadly speaking, grinding burn refers to discoloration or transmutation of the grinding surface, however this study particularly focuses on the change in metallographic structure (re-quenched and tempered layer) caused by grinding heat. These have a large impact on the fatigue strength of workpieces. The nitric acid etching method conventionally used to inspect for grinding burn on the production floor has several disadvantages, including varying detection levels between different people or equipment, and not being able to inspect all parts due to being a destructive test. As such there is a strong demand for the development of a non-destructive type of grinding burn detection system able to inspect 100% of workpieces and unrelated to the operator's individual experience. There are a number of non-destructive inspection methods for grinding burn[1-4] however, when considering implementation in the production line for 100% of workpieces, measurement time and equipment cost are important elements in addition to detection sensitivity. In this study, it was deemed that a method using eddy current had potential so we developed a Grinding Burn Detection System utilizing an eddy current sensor.

2. Detection principle

Figure 1[5] shows the cross-sections and hardness of two test pieces (material: SUJ2) with differing degrees of grinding burn. The dark, discolored portions are equivalent to portions where the material has been softened due to grinding heat (hereafter referred to as the "tempered layer"). If there is a significant degree of grinding burn, in addition to the forming of tempered layers, the outermost surface layer may reharden (hereafter referred to as the "re-quenched layer"). Although this portion has higher hardness than the tempered layer, it is extremely brittle, therefore both tempered layers and re-quenched layers are causes of reduced fatigue strength. Apart from martensite, the metallographic structure of the test pieces contains austenite (retained austenite) which did not mutate following quenching and tempering. **Figure 2**[5] shows the results of measuring the retained austenite for 3 types of test pieces (material: SUJ2). It is evident that the amount of retained austenite does not change in depth from the surface when there is an absence of grinding burn, however does decrease in the tempered layer and increases in the re-quenched layer. In this way it is possible to detect tempered layers by measuring the tretained austenite. Retained austenite is a non-magnetic structure[6] therefore has a different magnetic permeability to other structures.

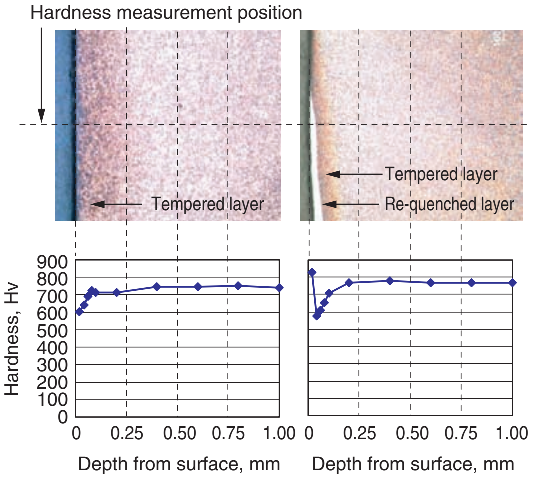

Fig. 1 Etched cross section of test pieces and hardness[5)]

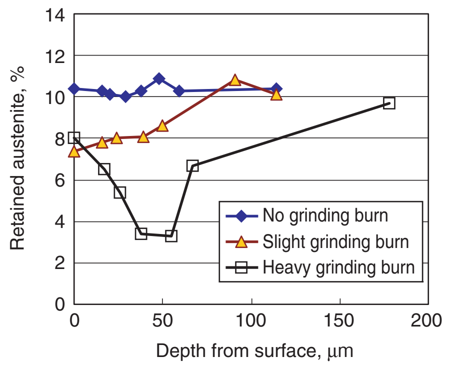

Fig. 2 Retained austenite content versus depth from top surface[5)]

Eddy current sensors use electromagnetic induction generate an eddy current in a conductor and detect the magnetic field created by the eddy current as a change in coil impedance. The sensor makes it possible to detect grinding burn as the flow of eddy current will change due to differing magnetic permeability of the portions with grinding burn as opposed to that of the portions without grinding burn. **Figure 3** is a simplified diagram of the eddy current sensor used in this study. As **Fig. 3** shows, it is a bridge circuit comprising of a coil for excitation and detection, a calibration coil and two variable resistances. Output is the potential difference V between terminals ab. In the actual measurement, a master workpiece is prepared and its measured value made the benchmark to compare with measured values from the test pieces and see the degree of difference. Regarding the impedance of the coil for excitation and detection, Z_S is used if nothing is measured (the test piece is far enough away from the sensor), $Z_S+\Delta Z_{Sm}$ is used for measurement of the master workpiece, $Z_S+\Delta Z_{Sw}$ is used for measurement of the test piece, and furthermore if the output between terminals ab at the time of master workpiece measurement is made V_m the output between terminals ab at the time of measuring the workpiece for inspection is made V_w the eddy current output $V_{current}$ is defined in the following way.

$$V_{current} = V_m - V_w = \frac{(\Delta Z_{Sm} - \Delta Z_{Sw}) Z_C}{(Z_S + \Delta Z_{Sm} + Z_C)(Z_S + \Delta Z_{Sw} + Z_C)} E \quad (1)$$

Here, E is the power source voltage while Z_C is the impedance of the calibration coil. Moreover, a feature of the eddy current sensor is that the depth that eddy currents penetrates into the material can be controlled by changing the excitation frequency. The standard depth of penetration (the depth at which eddy current density decreases to approximately 37% compared with that of top surface) δ is expressed in the following formula.

$$\delta = \frac{1}{\sqrt{\pi f \mu \sigma}} \quad (2)$$

Here, f is the excitation frequency, μ is the magnetic permeability and σ is the electrical conductivity. Therefore, detection of an even higher accuracy is possible by setting the excitation frequency to suit the depth of the defect to be detected from the surface.

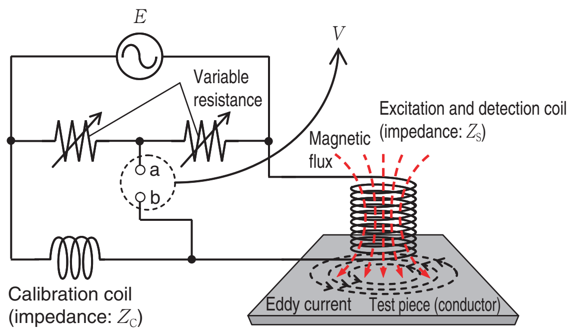

Fig. 3 A simplified diagram of the eddy current sensor system

3. Base material variance and the multi frequency measurement

Figure 4 shows the results of measuring the eddy current output in the outer race of three ball bearings from different manufacturing lots. As shown to the left in **Fig. 4**, the eddy current output of the circumference face was measured while the ball bearing outer trajectory was being rotated. Test pieces 1 and 2 are free of grinding burn, while grinding burn was intentionally created on test piece 3 by changing the grinding conditions when machining the outer periphery face. There is practically no difference in the eddy current outputs of test piece 2 (no grinding burn) and test piece 3 (with grinding burn), therefore it is obvious that it is difficult to determine the presence of grinding burn. This is because there is variation in the amount of retained austenite in the base material, and in order to detect grinding burn, rather than the absolute value of the retained austenite, it is necessary to detect the decrease in retained austenite (difference between the retained austenite in the base material compared to that in the tempered layer).

Therefore, as shown in **Fig. 5**[5)], this study devises a method to detect grinding burn by performing a measurement with deeper penetration and lower excitation frequency in order to suppress the impact of variation in retained austenite of the base material, and at the same time, perform as high excitation frequency measurement to detect grinding burn, then correlating the results of the two excitation frequencies. If there is a significant difference between the eddy current output at low excitation frequency and the eddy current output at high excitation frequency, there is grinding burn. However, if the difference in eddy current output is small, grinding burn is deemed to be absent. We selected 0.5 kHz as the excitation frequency to be sufficiently low, as the eddy current output is impacted by the base material. We selected 250 kHz for the high excitation frequency so that tempered layers could be detected even if re-quenched layers occurred. **Figure 6** shows an example of measuring eddy current output using two frequencies (multi frequency measurement) on the same test pieces as those used in **Fig. 4**. If there is grinding burn, the eddy current output of 250 kHz will be greater in the negative than the eddy current output of 0.5 kHz, and a signal will appear in the bottom right, as shown in **Fig. 6**. It can be seen that the grinding burn which could not be detected in **Fig. 4** can be detected by using this method.

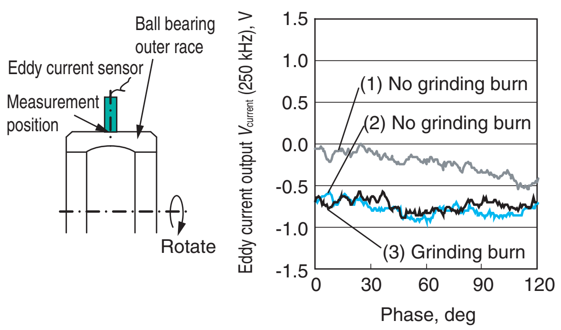

Fig. 4 Influence of dispersion of material properties[5)]

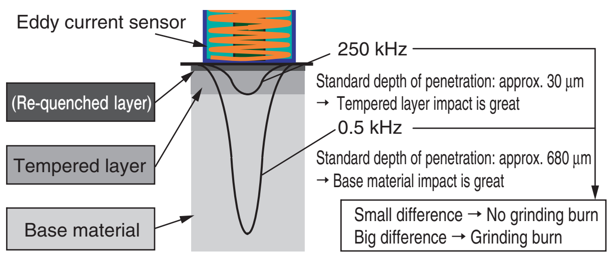

Fig. 5 Schematic view of multi frequency measurement[5)]

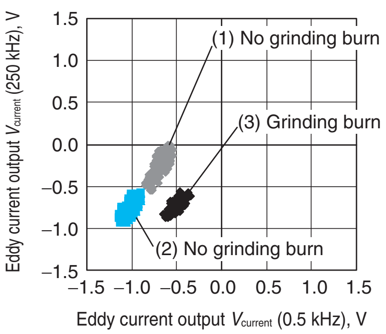

Fig. 6 Results by multi frequency measurement[5)]

4. Prevention of thermal drift

As **Fig. 7** shows, the phase has been adjusted in this study in order to suppress the thermal drift of the eddy current sensor[7)]. The output V of the eddy current sensor is the vector quantity and can be expressed in a complex plane, as shown in **Fig. 7**. The vertical axis shows the imaginary component of V (Im [V]), and the horizontal axis shows the actual component (Re [V]). Here, it is assumed that the temperature fluctuation of the coil for excitation/detection and the calibration coil occurs due to the temperature of the test piece. Here, signals are shown for the respective measurements of V_m, the master workpiece, $V_{w\text{-}S}$, the test piece with only slight grinding burn, and $V_{w\text{-}L}$, the test piece with significant grinding burn. As shown in the left of **Fig. 7**, V movements in the complex plane differ depending on if the cause is temperature fluctuation or grinding burn. Here, because the complex plane movement due to temperature fluctuation is linear, as shown in the right of **Fig. 7**, by rotating the phase so that the movement of the signal caused by temperature fluctuation is parallel with the horizontal axis and only making the imaginary component (Im [V]) a valid output, it is possible to suppress the impact of temperature fluctuation on the output of the eddy current sensor. The movement on the complex plane of eddy current sensor output in relation to temperature fluctuation varies depending on sensor specifications, excitation frequency, test piece material and so on. As such, it is necessary to find the rotation angle of $\Delta\theta$ through experimentation when performing phase adjustment.

In summary, through the method of suppressing disturbance caused by test piece temperature fluctuation explained in this section, and through a multi frequency measurement method which suppresses the influence of variation in the base material structure, as discussed in **section 3**, this research uses the evaluation function V_d, shown in the following equation, as a parameter used in detecting grinding burn.

$$V_d = \mathrm{Im}\left[V_{current}\left(f = 250\ \mathrm{kHz}, \Delta\theta = \Delta\theta_{250}\right)\right] - \mathrm{Im}\left[V_{current}\left(f = 0.5\ \mathrm{kHz}, \Delta\theta = \Delta\theta_{0.5}\right)\right] \quad (3)$$

Here, $V_{current}$ is the eddy current output expressed in equation (1), f is excitation frequency, $\Delta\theta$ is the rotation angle of the phase and $\Delta\theta250$, $\Delta\theta0.5$ are constants which suit the sensor specifications found through experimentation.

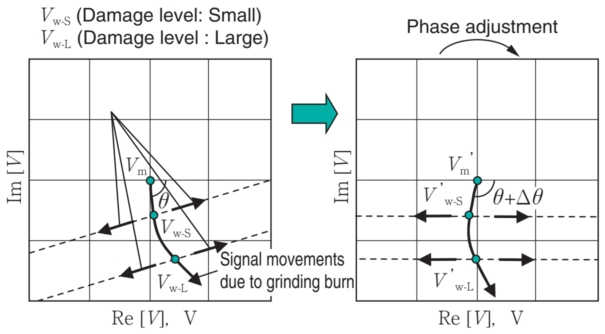

Fig. 7 Prevention of thermal drift

5. Prototyping a Grinding Burn Detection Device

5. 1 System overview

We prototyped a device to apply the grinding burn detection technology mentioned above. **Figure 8** is a schematic of this device. This device is configured from an eddy current sensor, excitation/detection device, drive device and data collection device. The tip of the eddy current sensor is L-shaped and the preload mechanism of the measurement jig holding the sensor prevents the gap between the sensor and test piece from changing by applying a consistent force.

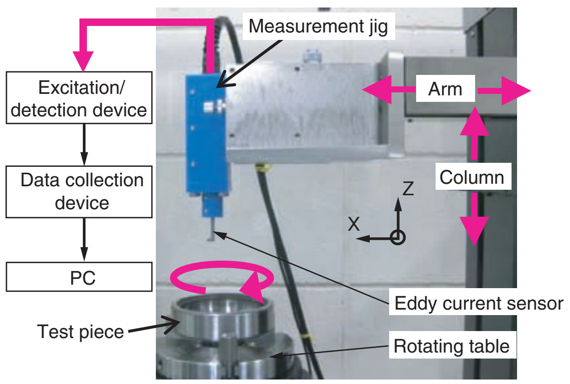

Fig. 8 Schematic of grinding burn detection device[7)]

5. 2 Implementation examples

Figures 9 and **10** are examples of grinding burn detection using the prototyped grinding burn detection unit. **Figure 9** shows the detection results obtained by using nitric acid etching (upper) and our prototyped device (lower) respectively on the circumference of a cylindrical test piece (material: SUJ2) which developed grinding burn during the grinding process. In the measurement results of our prototyped device, the greater a negative the evaluation function V_d is, the blacker the color, hence the portions of the test piece with grinding burn are displayed in black. **Figure 9** clearly shows that by using our prototyped device, it was possible not only to detect grinding burn in places undetected by nitric acid etching (phases 0° to 90° and 180° to 270° of the test piece), but also minute changes in the metallographic structure undetectable using nitric acid etching.

Therefore, it can be said that a higher accuracy of grinding burn detection is possible using an eddy current sensor, compared to the nitric acid etching form of detection. By comparing the results obtained from nitric acid etching and the results obtained by using our prototyped device, from here on we established the threshold of grinding burn being present or absent as V_d = -0.5 V. **Figure 10** shows the results of evaluating grinding burn presence/absence in the raceway surface of a ball bearing outer race (material: SUJ2) following the grinding process. A total of 26 workpieces were measured here, comprising of 25 workpieces from the production plant and 1 test piece ground in a way that would deliberately cause grinding burn. All workpieces were demagnetized prior to measurement. Moreover, measurements were performed by putting the eddy current sensor in contact with the bottom of the raceway surface as shown in **Fig. 10** and doing one full circle while rotating the workpiece being measured. The prototyped device was placed in a non-air conditioned room within the plant and the maximum temperature change of the measured workpieces at the time of measurement was 3.9°C. The eddy current output is 250 kHz excitation frequency on the vertical axis and 0.5 kHz on the horizontal axis, with the results shown in the bottom section of **Fig. 10**. If the threshold is set as V_d = -0.5 V, it means grinding burn has occurred if the measured value is plotted below the V_d = -0.5 V line in the graph, and no grinding burn has occurred if above the V_d = -0.5 V line. **Figure 10** shows that no grinding burn was detected in the workpieces from the production line measured in this sample however the test piece for which grinding conditions were intentionally altered did have grinding burn. Moreover, the output value of the eddy current sensor for the 25 workpieces from the production line had variation of around ±0.3 V however by using the prototyped device, it was possible to detect grinding burn without false judgment. In this experiment (**Fig. 10**), on top of suppressing the effect of disturbance due to temperature, the temperature change of the test piece itself and the room temperature during the test was small, therefore it is believed that the impact of temperature on the measurement results was sufficiently small.

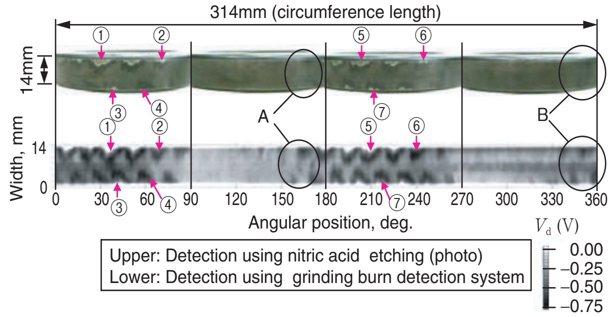

Fig. 9 Grinding burn detection in circumference of a workpiece

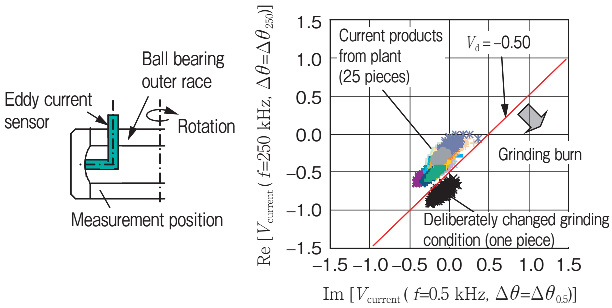

Fig. 10 Grinding burn detection in raceway surface of outer race[7]

6. Conclusion

This study involved the proposal and verification of a grinding burn detection method and unit using an eddy current sensor as a technology to detect grinding burn through the non-destructive inspection of 100% of parts. The following knowledge was obtained from this study.

(1) In regards to the excitation frequency, a high frequency to detect the state of the test piece's surface, and a low frequency to detect the state of the base material were used. By comparing the difference in the measured values of these two frequencies it is possible to suppress the impact of the variation in the base material structure.

(2) By ascertaining the change in output of the eddy current sensor due to temperature change, it is possible to suitably adjust the eddy current sensor output phase, and by making only either the actual component or imaginary component valid outputs, it is possible to suppress the impact of temperature change.

(3) In the grinding burn detection test on a ball bearing, by applying this detection technology, it is possible to detect grinding burn quantitatively and at a higher accuracy than nitric acid etching.

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