

Development of Hardening Depth Evaluation Technique using Eddy Current – Establishment and Introduction of In-line Hardening Depth Inspection System –

Takanari Yamamoto and Tetsuya Yamaguchi
Toyota Motor Corporation

Copyright © 2009 SAE International

ABSTRACT

A hardening depth evaluation technique using eddy current has been developed, which can be applied to a mass production line for destructive (cutting) inspections. Using this technique, changes in the hardness of the induction-hardened structure can be detected based on the changes in magnetic permeability. This technique reduces the thermal effect and improves measurement accuracy through a multi-frequency exciting method and a difference method algorithm.

1. BACKGROUND OF DEVELOPMENT

1-1 CURRENT STATE OF INDUCTION HARDENING QUALITY ASSURANCE - Induction hardening is a widely used technique for improving the wear resistance and fatigue strength of chassis components and other high strength members that support the driving, turning, and stopping performance of the vehicle. In addition, an important quality control index for these parts is hardening depth, i.e., the distance from the surface that the induction-hardened structure maintains a certain value. However, the quality of the structure can only be evaluated at the production site through destructive inspections that requires cutting the part to measure the hardening depth and the degree of surface hardness. This leads to the following issues.

1. Part inspection is done through sampling (not all parts can be inspected)
2. Inspection is time consuming and cannot be performed efficiently
3. Higher cost for the inspected parts which are scrapped regardless of their results

For these reasons, to develop a simple and non-destructive technique capable of 100% inspection of the hardening depth of select parts in a mass production line has been developed.

1-2 DETAILS OF DEVELOPMENT - Several non-destructive techniques for evaluating hardening depth have already been researched and commercialized including ultrasonic methods⁽¹⁾⁻⁽⁵⁾, direct-current potential-drop methods⁽⁶⁾⁽⁷⁾, alternating current potential-drop methods⁽⁸⁾ and Barkhausen noise methods⁽⁹⁾. However, due to the poor measurement accuracy, the requirement of couplant as a measurement condition, the incapability of non-contact measurement, and the long processing times, none of the techniques have been applied to in-line inspection. Therefore, at the early stage of the development, we focused on eddy current, which is capable for non-contact and high speed measurement and believed that it is one of the most promising candidates for extensive in-line inspection⁽¹⁰⁾. However, since eddy current is extremely sensitive to the environmental and part temperatures, technology transformation from laboratory condition⁽¹¹⁾⁽¹²⁾ to a mass production environment is greatly limited, and the so-called thermal effect must be reduced before introducing the eddy current measurement to the production line.

In order to solve this problem, we developed a multi-frequency exciting method and a difference method algorithm and successfully introduced the world's first robust eddy current measurement technique into mass production for 100% in-line inspection of the hardening depth of select parts. For over a year, this technique has functioned stably under the mass production environment at a normal operation condition. This paper

describes the development of applying this technique into an induction hardening depth eddy current measurement system and its practical application to a mass production line.

2. OUTLINE OF EDDY CURRENT MEASUREMENT

2-1 PRINCIPLE OF HARDENING DEPTH DETECTION

The developed eddy current measurement technique detects the changes in the induction-hardened structure as fluctuations by measuring permeability μ , i.e., the magnetic properties of the material. **Fig.1** shows the relationship between the hardness of the induction-hardened structure and permeability. When a material (usually carbon steel) is induction-hardened, the following layers are formed in sequence from the surface to create the induction-hardened structure: martensite $\rightarrow$ troostite $\rightarrow$ sorbite $\rightarrow$ ferrite + pearlite. Martensite is the hardest layer, followed by the troostite, sorbite, and ferrite + pearlite layers. Permeability has an inverse relationship to hardness and increases in sequence from the martensite layer through the troostite, sorbite, and ferrite + pearlite layers⁽¹³⁾. Using eddy current to detect fluctuations in permeability based on this relationship is the foundation of this technique.

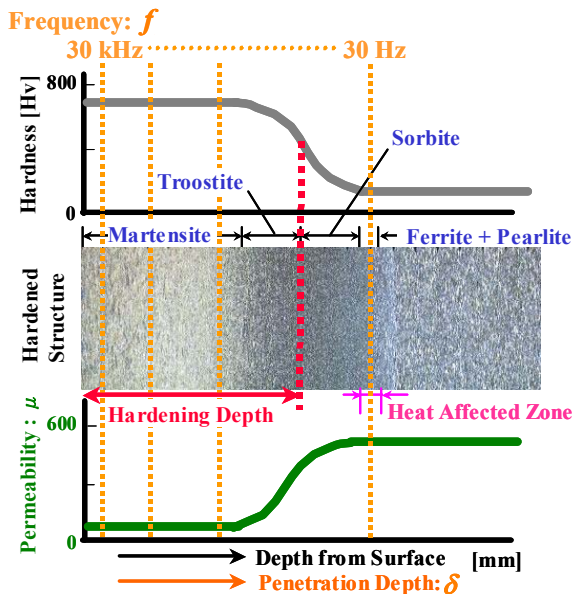


Fig.1: Relationship of Induction-hardened Structure Hardness, and Permeability

2-2 MEASUREMENT METHOD - An induction-hardened part (a conductor) is inserted into an encircling coil, which consists of an exciting coil and a detecting coil. When alternating current (AC) passes through the exciting coil, an AC magnetic field (i.e., a magnetic field that fluctuates in accordance with time) is generated. And the eddy current on the part surface due to the magnetic flux through the part is induced. **Fig.2** shows an outline of eddy current measurement using the exciting coil. The eddy current is affected by the electromagnetic properties of the part (permeability

μ_{parts} and electrical conductivity σ_{parts}) and causes a demagnetizing field to be generated in the direction opposite to the fluctuations in magnetic flux. These fluctuations in magnetic flux caused by eddy current are detected by the detecting coil through the changes in electromotive force. The phase difference and amplitude of the detecting waveform are expressed as eddy current output values (X, Y, see **Fig.3**). Here, the fluctuations in electromotive force ΔV at both ends of the detecting coil can be calculated by the following equation from Faraday's law of induction, where V_0 and Φ_0 are the electromotive force and magnetic flux of the part before the insertion into the detecting coil, and V_1 and Φ_1 are the electromotive force and magnetic flux after the insertion, respectively.

$$\begin{aligned}\Delta V &= V_0 - V_1 = -N \frac{\Delta \Phi_0}{\Delta t} - \left(-N \frac{\Delta \Phi_1}{\Delta t} \right) \\ &= -N \cdot S \frac{\Delta B_{\text{coil}}}{\Delta t} - \left\{ -N \cdot S \left(\frac{\Delta B_{\text{coil}}}{\Delta t} - \frac{\Delta B_{\text{parts}}}{\Delta t} \right) \right\} \\ &= -N \cdot S \frac{\Delta B_{\text{parts}}}{\Delta t}\end{aligned}\quad (1)$$

Here N is number of coil turns, S is sectional area of coil, B_{coil} is magnetic flux density due to AC magnetic field of exciting coil, and B_{parts} is magnetic flux density due to demagnetizing field of eddy current.

Since the magnetic flux density due to the demagnetizing field of the eddy current B_{parts} has a proportional relationship with the permeability of the part μ_{parts} , fluctuations in electromagnetic force ΔV are small if μ_{parts} is low (i.e., if the induction-hardened structure is hard, as shown in **Fig.1**). In this case, the amplitude Y of the detecting waveform used for eddy current measurement is also small.

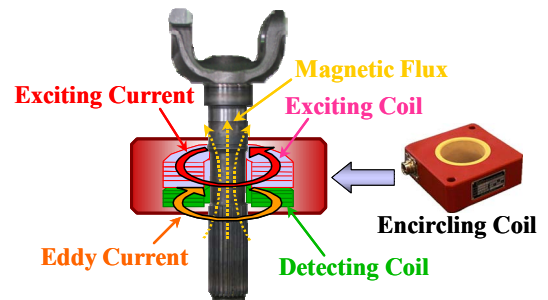


Fig.2: Eddy Current Measurement Method

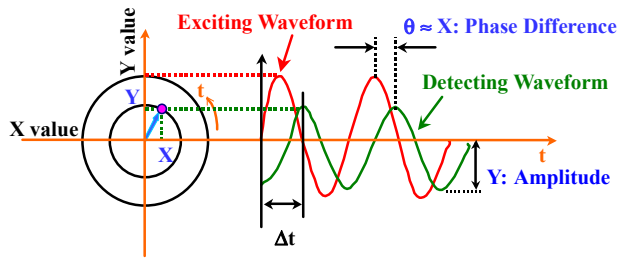


Fig.3: Parameterization of Detected Waveform

In contrast, the penetration depth δ of the eddy current, which provides the index for obtaining the depth to which the eddy current has penetrated inside the part, can be calculated using equation (2). Here, the penetration depth δ refers to the depth at which the strength of the eddy current is calculated to be $1/e \approx 37\%$ based on the eddy current at the surface of the conductor.

$$\delta = \frac{1}{\sqrt{\pi \cdot f \cdot \mu_{\text{parts}} \cdot \sigma_{\text{parts}}}} \quad (2)$$

Equation (2) shows that the penetration depth δ is inversely proportional to the square root of the exciting frequency f , the permeability of the part μ_{parts} , and the conductivity of the part σ_{parts} . Thus, the smaller the exciting frequency becomes, the deeper the penetration of the eddy current reaches, and the greater the amount of data that can be obtained on the internal properties of the part (**Fig.1**).

In addition, the phase difference $\theta \approx X$ as shown in **Fig.3** can be expressed by equation (3), and it is already known that the phase difference of eddy current increases in proportion to the depth d from the surface of a conductor⁽¹⁴⁾.

$$\theta = d \cdot \sqrt{\pi \cdot f \cdot \mu_{\text{parts}} \cdot \sigma_{\text{parts}}} = \frac{d}{\delta} \quad (3)$$

The results shown in **Fig.4** and **Fig.5** demonstrated that the eddy current output values (X, Y) are closely correlated with hardening depth and surface hardness.

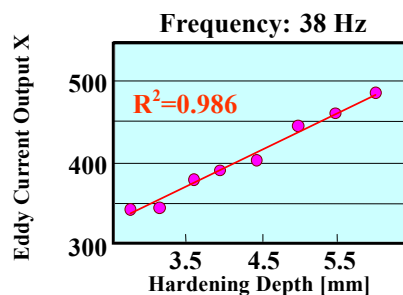


Fig.4: Relationship of Hardening Depth and Eddy Current Output X

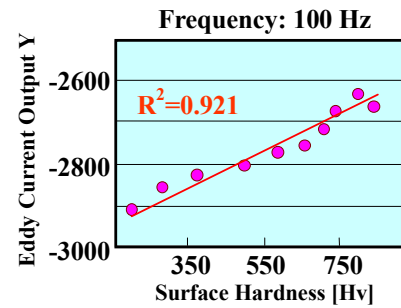


Fig.5: Relationship of Surface Hardness and Eddy Current Output Y

Unlike other testers and measurement instrumentation, the non-destructive measurement techniques such as eddy current do not directly measure the absolute value of the basic physical quantities such as voltage, temperature, or frequency, in order to quantify an unknown value, a calibration curve, as shown in **Fig.4** and **Fig.5**, obtained by measuring the samples with already known hardness values is required. With this calibration curve, the hardening depth and surface hardness can be calculated based on the eddy current output values (X, Y) obtained from the target part. When measuring hardening depth, low exciting frequencies are used to increase the amount of data obtained from the inside of the part. When measuring surface hardness, high exciting frequencies are used to concentrate the eddy current near the surface.

3. DEVELOPMENT KEY POINTS

3-1 ADOPTION OF MULTI-FREQUENCY EXCITING METHOD - When measuring hardening depth using eddy current, usually, only one single low-frequency excitation is used for obtaining a penetration depth near the base material layer. Since hardening depth must be evaluated within the regulated range (several millimeters in width), the data obtained from a single frequency alone may limit the measurement accuracy. Furthermore, because the maximum differences of temperature can reach to 40°C between the parts at normal operation and cold start conditions, if the eddy current is measured immediately after the induction hardening process, the thermal effect significantly affects the detection result calculated from the single frequency calibration curve (**Fig.6**). Therefore, the multi-frequency exciting method was developed in order to remove this thermal effect. **Fig.7** shows an image of single and multiple frequencies.

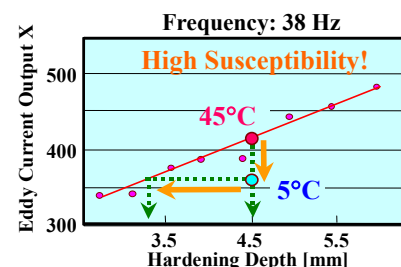


Fig.6: Influence of Temperature on Calibration