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HARDENING EVALUATION OF CARBON STEEL BY USING FREQUENCY SWEEPING EXCITATION AND SPECTROGRAM METHOD

Taisuke Matsuda* —Yuji Tsuchida* —Takashi Todaka* —Masato Enokizono*—Yuichiro Kai**

Induction heating is a very effective hardening method to improve strength of carbon steels, which are usually used as a structural material. However, the current method for testing the hardening requires time and effort. Therefore, the non-destructive evaluation of the hardening condition is desired. This paper presents a magnetic evaluation method of hardened carbon steels by using the frequency sweeping excitation and spectrogram (FSES) method.

Keywords: hardening, non destructive evaluation, magnetic properties, frequency sweeping excitation and spectrogram method

1 INTRODUCTION

Carbon steels are often used as main structural materials which are hardened to improve their strength. High frequency induction heating method is a very effective hardening method to improve strength of carbon steels. However, the hardening method improves strength of carbon steels by the risk of increasing brittleness. In addition, this effect by high frequency induction heating depends on the hardening depth and hardness. Therefore it is important to estimate the hardening depth and the hardness in evaluation.

Presently, hardening depth and hardness of specimens are examined by mechanical hardness tests. These tests need reference samples because the samples must be destroyed for the measurements. Therefore, the non-destructive evaluation is desired. If we can estimate the hardening depth and hardness non-destructively, we can control the hardening depth and hardness and prevent accidents due to brittleness. However non-destructive evaluation of hardening depth and hardness is very difficult and the various studies that have used an electromagnetic technique have been done so far [1]. In the previous studies, it was found that the magnetic properties were changed depending on hardening conditions [2-4]. And, the frequency sweeping excitation and spectrogram (FSES) method was developed to evaluate the magnetic properties of the hardened carbon steels. This method was clarified applicable to evaluate difference of region and temperature of the hardened carbon steels. Problems of the previous evaluation method have quantitative evaluation of hardened depth and hardness and measurement of complicated shape samples.

In this paper, we evaluate the hardened carbon steel with the FSES method, and verify fundamental properties. Then, we applied our method to the practical car seat parts. We consider how quantitative evaluation of the hardness and depth of hardening. In addition, some parts on the surface were hardened and rugged by hardening. Finally, we examined the evaluation method whether it can be applied to the practical products or not.

2 PRINCIPLE OF FSES METHOD

Figure 1 shows the principle of the FSES method. The concept of the FSES method based on frequency dependence of magnetic property changes in hardened carbon steels. As shown in Fig. 1, these f_1, f_2, f_3, •••, f_n are the frequency components and n is the number of the excitation frequency. This method uses a lot of frequency components for exciting wave. The magnetic flux penetration depth (skin depth δ) changes depending on the frequency. δ can be expressed by the following equation

$$\delta = \frac{1}{\sqrt{\pi f \mu \sigma}} \tag{1}$$

Where, f is the exciting frequency, μ is the relative permeability and σ is the conductivity. Fig. 2 shows the relation between δ and frequency. The penetration depth changes depending on the frequency strongly. As shown in the equation (1), the skin depth influences μ and σ. Hardened region is known to change magnetic properties. FSES method that uses many frequency components therefore it is possible to evaluate the magnetic properties depending on the frequency and information in the direction of depth. And by using the spectrogram method, we can obtain the hardening conditions depending on frequency visually. This method can express the change by the color. In this study, we evaluate the hardening with FSES method.

3 MEASUREMENT METHOD AND SPECIMEN

Figure 3 shows the structure of the magnetic sensor. The excitation coil and pickup coil are set up at both ends of sensor. The two pickup coils are connected cumulatively.

The exciting current that changes by the excitation frequency and the magnetic properties of specimen is constantly controlled. And, the induced voltage (peak-to-peak value) of the two pickup coils is measured. After that, we evaluate with the spectrogram method by using the induced voltages.

* Faculty of Engineering, Oita University, ** Oita Prefectural Organization for Industry Creation and Oita University, 700 Dannoharu, Oita 870-1123, Japan; v10e2032@oita-u.ac.jp

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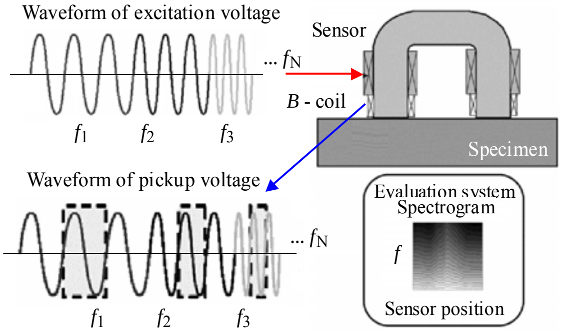

Fig. 1. Principle of FSES method

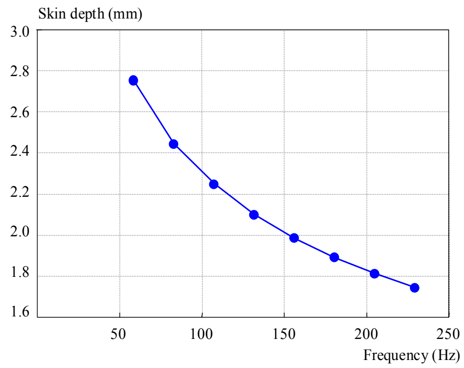

Fig. 2. Skin depth depending on frequency

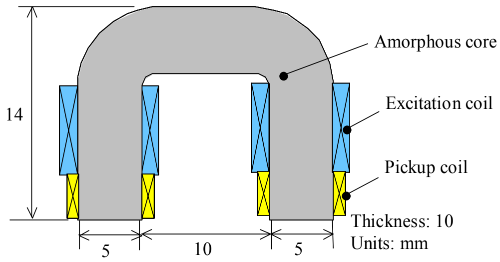

Fig. 3. Structure of magnetic sensor

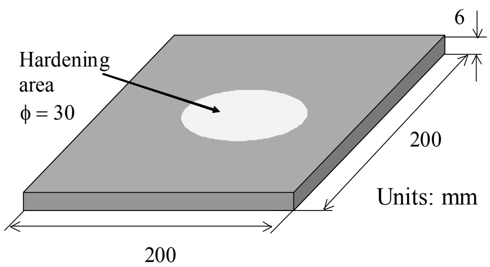

Fig. 4. Carbon steel plate (Sample-1)

Figure 4 and 5 show the schematic view of the specimen used in the measurement. Fig. 4 shows the carbon steel plate (Sample-1) is hardened in central part by using a high frequency induction heating. Figure 5 shows the specimen which is practical car seat parts. There are two kinds of the samples about hardening sample (Sample-A) and non-hardening sample (Sample-B). These specimens are created from two thin carbon steels and press working. Each sample is measured the position in the three places. The Position-1 is both samples are not hardened. At the Position-2, the Sample-A is hardening, the Sample-B is not hardening. The Position-3 condition is similar to the Position-2, but the surface of the Sample-A is raggedness by hardening.

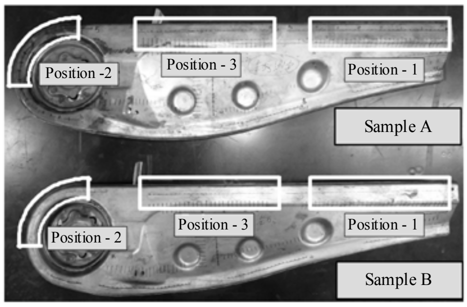

Fig. 5. Practical car seat parts

4 MEASURED RESULTS

4.1 Fundamental properties of the hardening evaluation by FSES method

Firstly, we verified the fundamental properties of FSES method by measuring the sample-1, Fig. 4, and the influence by the 1mm lift-off is shown.

Figure 6 shows the measured results of the Sample-1. From the Fig. 6(a) and 6(b), it is clear that the difference appeared in the hardened region, because the permeability and the conductivity in the hardened region were decreased. This method is effective to make clear the hardening conditions visually.

Figure 7 shows the measured results of the Sample-1 that considers 1mm lift-off. From the Fig. 7(a) and 7(b), it is clear that the difference appeared in the hardened region. The influence of induced voltage was large at high frequency. As a result, it is possible to evaluate the hardened region and the hardening degree even with the 1-mm lift-off.

4.2 Evaluation of practical car seat parts

It was shown that our method was effective for the hardening evaluation. Next, we applied our method to the practical car seat parts (Fig. 5). Figure 8 shows the results of the Position-1. From the figures, the two spectrograms are almost same. Therefore, we can estimate that the material conditions of the two samples are almost same.

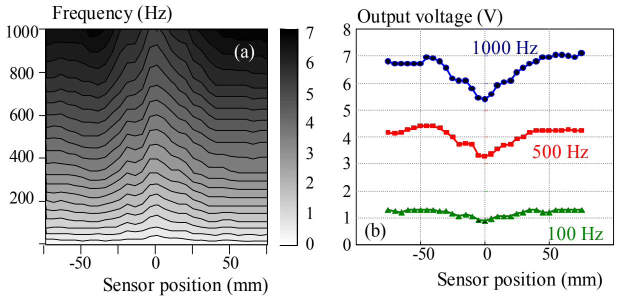

Fig. 6. Spectrogram of the Sample-1: (a) – Spectrogram, (b) – pickup voltage

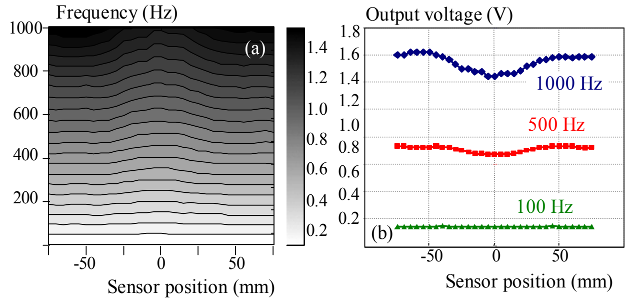

Fig. 7. Spectrogram of the Sample-1 (1[mm] lift-off): : (a) – Spectrogram, (b) – pickup voltage

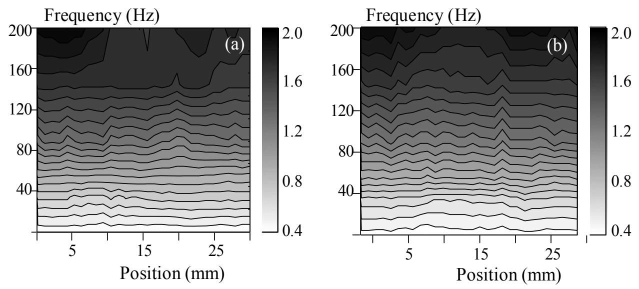

Fig. 8. Spectrogram of the car seat parts (Position-1): (a) - Hardening, (b) - Non-hardening

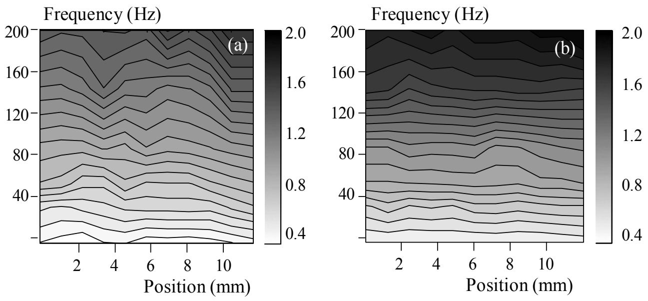

Fig. 9. Spectrogram of the car seat parts (Position-2): (a) - Hardening, (b) - Non-hardening

Figure 9 shows the results of the Position-2. From the figures, the spectrograms of the hardening and non-hardening positions are different. Fig. 9(a) shows the spectrogram value was decreased. In the case of the hardened sample, it is estimate that the magnetic properties were changed. From the results of the Position-1 and the Position-2, we can distinguish the hardened region.

4.3 Quantitative evaluation by ratio of frequency

This method can evaluate the difference of the hardened region even with the practical car seat parts. In order to detail the hardening evaluation, we tried to quantitative evaluation of the hardened degree and depth. Fig. 10 shows the principle chart of the evaluation method. Firstly, we selected arbitrary voltage in the spectrogram as the specific point. Next, the vertical axis of the spectrogram is normalized as 0 to 100. After that, the ratio of the length (L_1:L_2) from the upside and the downside to the selected point is calculated at each measured position. Finally, L_2 is decided normalized value and the graph is made. Figure 11 shows the result of the Position-1. From

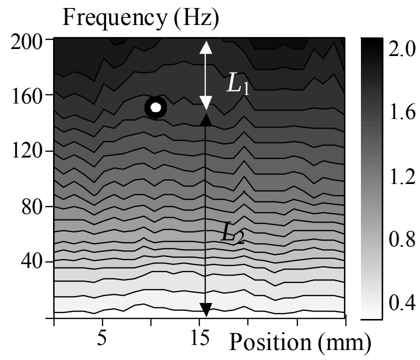

Fig. 10. Principle of quantitative evaluation

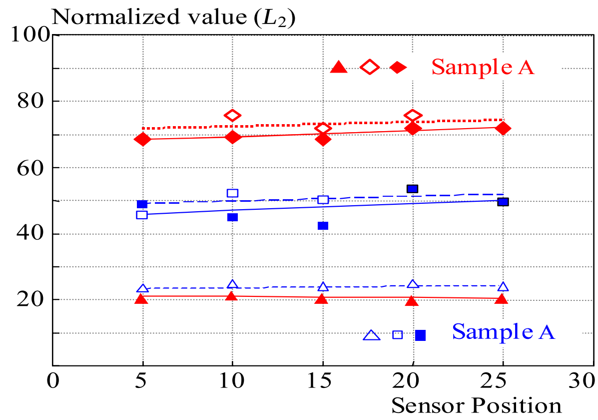

Fig. 11. Quantitative evaluation of the Position-1

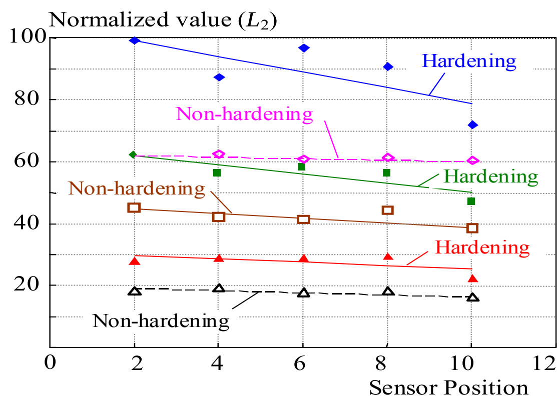

Fig. 12. Quantitative evaluation of the Position-2

this figure, the solid lines are Sample-A (non-hardening), the dotted lines are Sample-B (non-hardening). The solid lines and the dotted lines are nearly same. Therefore, it is clear that the two spectrograms are almost same. By using this evaluation method, we can compare hardened conditions quantitatively. The evaluation with spectrograms is useful to obtain the difference of hardened conditions visually. Figure 12 shows the result of spectrogram at thePosition-2. From this figure, the solid lines are Sample-A (hardening), the dotted lines are Sample-B (non-hardening). The solid lines were declined on the right hand, and approach the dotted lines. Therefore, it is estimated that the hardened degree and depth are decreased in the right position. As a result, the quantitative compare and evaluation of hardening condition is possible.

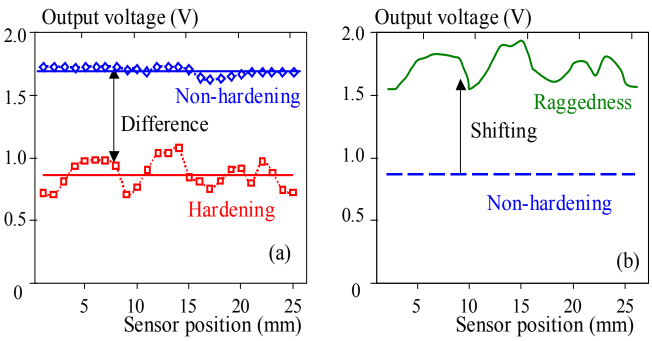

Fig. 13. Distinguishing the ruggedness and the hardening conditions: (a) - Calculated and average values, (b) - Distinguished signals

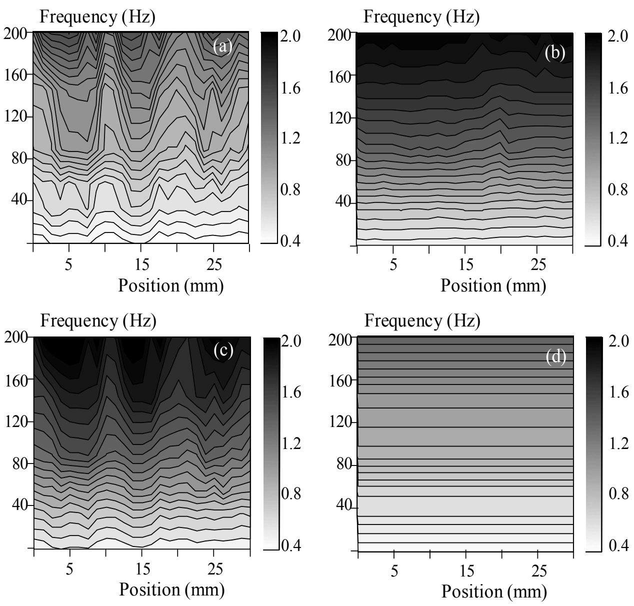

Fig. 14. Spectrogram of hardened and rugged samples: (a) - A (hardening + ruggedness), (b) - B (non-hardening signals), (c) – Ruggedness, (d) - Hardening conditions

4.4. Evaluation of the rugged surface

The induced voltage showed that the lift-off strongly influenced. In the Position-3 of the Sample-A, there is ruggedness on the surface the influence of the ruggedness detection to the output signal. As a result, an accurate hardening evaluation is impossible. In addition, the induced voltage influences hardening conditions. The induced voltage is influence by the two factors strongly, hardening conditions and surface conditions. Therefore, it is necessary to distinguish them for practical hardening evaluation. Then, we tried to distinguish the signals by the raggedness and the hardening conditions.

Figure 13 shows the distinguish method. Firstly, from the measurement results in the Position-3 to calculate the average value of output for each frequency obtained, Fig.13(a). Next, Sample-A (Hardening + Ruggedness) and Sample-B (Non-hardening) are calculate the difference between each average value, Fig .13(a). Then, it is shifted by the calculated value in which the measurement results of the Sample-A, Fig.13(b). Figure 13(b) shows the final obtained signal (wavy-line) can be estimated to be the signal caused by surface ruggedness. Then, the averaged signal (straight-line) becomes the signal caused by only hardening.

Figure 14 shows the results of the estimation of the ruggedness at the Position-3. Figure 14 (a) is the spectrogram of the Sample-A (hardening + ruggedness), (b) is the Sample-B (non-hardening), (c) is estimated ruggedness signals, and (d) is estimated hardening conditions signals. By using this procedure, it is possible to distinguish the signals of the non-hardening, Fig.14(b) and (c), and hardening, Fig.14(a) and (d), samples. In addition, it is also possible to distinguish the signals of the flat, Fig. 14(b) and (d), and rugged, Fig.14(a) and (d), surface samples. As these results, it is possible to hardened region can be evaluate, even if the sample surface is raggedness. Therefore, we can apply this evaluation method to practical products.

5 CONCLUSIONS

We can evaluate the difference of the hardened depth and the hardened region on the carbon steels without the lift-off and with a lift-off of 1mm, by using the FSES method. This method is useful to evaluate the hardening of practical car seat parts visually and quantitatively, although their surfaces are complicated.

In the future work, we will confirm the hardening degree of the measured samples by mechanical testing. And, we will apply our method to various product samples to develop a practical evaluation method of hardening.

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