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交流磁化プローブを用いた鋳造構造物の材質評価

Foundry Material Property Evaluation Employing AC Magnetization Probe

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This paper studies a method of non-destructive evaluation for the hardness of ductile cast irons employing an AC magnetization probe that evaluates the differences in magnetization characteristics. The analysis of the waveform obtained from the probe on the ductile cast iron specimens performs estimating their hardness since mechanical properties are strongly related to two factors: the graphite shape matrices mainly composed of pearlite and ferrite. The waveforms around Rayleigh region yield the essential parameters representing residual flux density, coercive force and hysteresis loss, showing the correlation with the hardness. Moreover, the 3rd harmonic FFT spectrum of detected voltage is considered. The hardness of ductile cast irons can be estimated by using these parameters with good accuracy. Thus, this new type of probe suggests one of the fast-and-quality systems for the maintenance of the foundry structures.

Keywords: ductile cast iron, foundry material, AC magnetization method, hardness evaluation.

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1. Introduction

Ductile cast iron is cast iron in which the graphite is present as tiny spheres: this feature permits greater strength and greater ductility than gray cast iron of similar composition. There are so many applications of ductile cast irons, for instance, automotive-crankshafts, pistons, motor frames, levels, furnace doors, electrical fittings, switch boxes and tools for aqueducts; then the nondestructive evaluation of its mechanical properties is of paramount importance for the maintenance of various kinds of apparatus as well as structures.

Two factors, the morphology of graphite and the type of matrices, mainly determine mechanical properties of cast irons. With the good sensitivity to graphite morphology, ultrasonic techniques have been used for the evaluation of mechanical properties in cast iron [1,2].

In case of ductile cast iron, mechanical properties depend on both the nodularity of the graphite and the properties of matrices. Because it is difficult for ultrasonic techniques to assess the structure of matrices, direct observation and destructive testing such as hardness tests are usually carried out in the final analysis [3,4]. Therefore, it is essentially required to develop methods to assess the properties of matrices by means of non-destructive evaluation [5]. The matrix of ductile cast iron consists of structure in term of proportions of pearlite and ferrite. As the quantity of pearlite increases, the strength and hardness of the material increase. The proportion of ferrite and pearlite to the materials principally determines ductility and impact properties.

Figure 1 shows the optical microscopy photos of four specimens with difference in hardness, 143 HB, 162 HB, 215 HB and 259 HB; white and gray colors indicate the ferrite and pearlite, respectively; moreover the dark "spots" show the graphite: it can be seen that the pearlite ratio increases as hardness increases. Since the ferrite and pearlite have difference in electric as well as magnetic materials, then non-destructive ways utilizing electromagnetic field phenomena make it possible to evaluate the properties of matrices.

There are some methods to evaluate the matrices in non-destructive way by using harmonic analysis of eddy current testing [6] and eddy current evaluation concentrated in the reversible region of initial magnetization curve [7]. This paper also considers the weakly magnetized region with a low intensity of excitation. This means that eddy current signal reflects on only the two parameters, namely, conductivity and permeability around Rayleigh region. Because of reversible region on magnetization, it guarantees in addition the reproducibility of experiment [8]. Considering the relation between the hardness and the structure of matrix, it is possible to estimate the hardness of ductile cast iron efficiently. In addition, the hardness covers several other properties of materials, as resistance to deformation, resistance to friction and abrasion. There are two main differences with eddy current testing. One is to use relatively lower frequency, in a range of 6-7 kHz, to catch permeability variation in each of hardness. The other is to employ the amplified 3rd harmonic component of sensor output voltage to easily distinguish the differences in hysteresis loops.

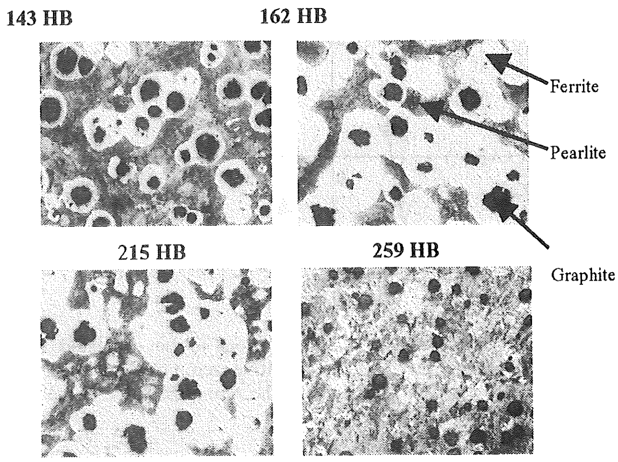


Figure 1: Example of microstructure of 4 ductile cast iron specimens with different hardness, 143 HB, 162 HB, 215 HB and 259 HB respectively. White and gray colors indicate the ferrite and pearlite, respectively. Dark "spots" indicate the graphite.

The AC magnetization probe used in this study includes simple data acquisition and good accuracy, in order to accommodate practical usage. To emphasize the permeability variation, the AC magnetization probe has a resonant circuit tuning up for about three times higher than the fundamental excitation frequency. It is an effective technique to assess the properties of matrices and it is expected a complete evaluation of mechanical properties of ductile cast iron. This nondestructive, as well as inexpensive approach can be realized through the combination of the present method with [6] for the matrices, and ultrasonic testing for graphite morphology.

2. AC magnetization method

The AC magnetization method consists of calculating magnetic flux density B[T] as a reaction of an alternating applied magnetic field H[A/m]. In the ferromagnetic materials the function $B = \mu H$ is not linear, it depends on the non-linearity of the permeability on varying of the magnetic field.

The initial magnetization curve is the relation between H and B for a ferromagnetic material virgin, which is material that has not had an influence of magnetic field yet. Figure 2 is a schematic diagram of the initial magnetization curve. Generally, it is possible to classify three zones of interest.

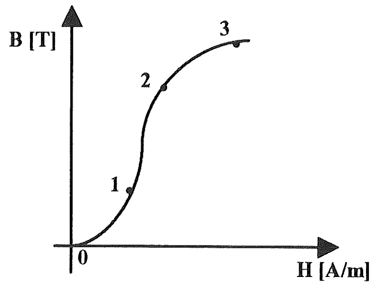


Figure 2: Initial magnetization curve: the points 1,2 and 3 indicate the division of the curve in three regions.

The region 0-1 is called reversible or Rayleigh region and it is considered in this investigation to guarantee the reproducibility of the measurements. In this region the material returns to its original state if a reversing magnetic field is applied. One of the principal problems is how to comprehend that the investigation is carrying out in the region. On the other hand, the regions 1-2 and 2-3 are non-reversible regions. In these regions, the residual effects of the magnetization, usually shown in the magnetic hysteresis loop (Figure 3), are exhibited, meaning that it is difficult to obtain good reproducibility without specific demagnetization preconditionings.

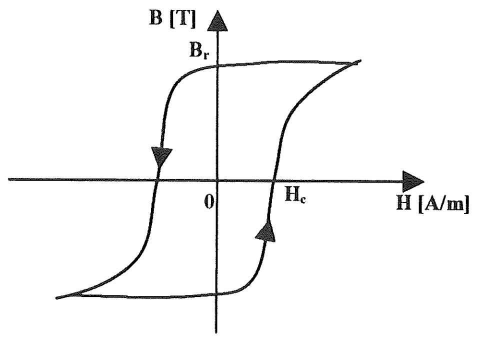


Figure 3: Hysteresis loop: the parameters to be evaluated in a hysteresis loop are the area, the positive zero-cross value of the magnetic field, called "coercivity" and the zero-cross value of the flux density, called "residual".

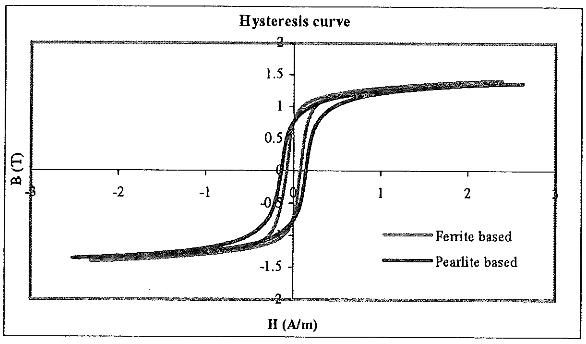


Figure 4: Hysteresis loops of Ferrite based and Pearlite based cast irons.

The hysteresis loop is the relation between the magnetic field H and the flux density B for a ferromagnetic material under an alternating magnetic field. In this case it is possible to observe that the magnetization curve traces different ways after the initial magnetization curve is overtaken. B_r, called residual, and H_c, called coercivity, represent the effects of the residual fields. The shape of the loop depends on the material and the area of the loop is proportional to the losses in term of energy.

Since the hysteresis loop changes its characteristics on changing the materials, then the AC magnetization approach uses those concepts to evaluate the properties of the materials. Figure 4 shows the differences in term of hysteresis loop for the ferrite- and pearlite- based cast irons. The pearlite-based cast iron presents a wider loop, meaning that it is hard in terms of magnetic and mechanical properties. In this case the probe with the 3rd harmonic amplified will be more sensible and the normalized value will be higher, as we will show in the experimental results. Furthermore the maximum value of B makes it possible to identify the structure of the matrix.

3. AC magnetization measurement system

The evaluation of cast irons was carried out with experimental setup showed schematically in Figure 5. The probe used in the system consists of two coaxial coils with differential connection [9].

The specimens were magnetized by supplying sinusoidal voltage to the probe at frequencies in a range of 6-7 kHz. The system presents the amplified 3rd harmonic of detected voltage by a circuit of which resonance frequency is about 18 kHz [10]. With the intention of show the differences of measurements in the non-resonance frequencies it was investigated also the 3kHz.

The exciting and detecting voltages, the values of the harmonics ratio in dB and the area of loop in Lissajous graphics were recorded by using a PCMCIA National Instrument DAQ Card 6062E; the software to control the excitation and detection, and to save the data on file was realized in LabVIEW 7.0 under a Laptop with 384 MB RAM and 1.13 GHz Intel Pentium III Processor.

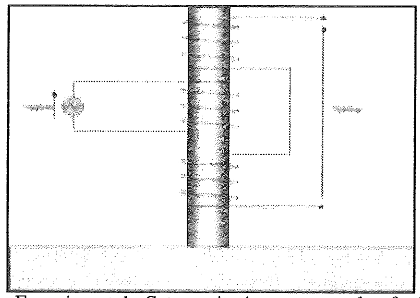


Figure 5: Experimental Setup: it is composed of the exciter, ferromagnetic core and system to detect the Vpickup.

All instrumentation weighs about 1 kg and takes up as a book: it guarantees the portability of the probe device. It consists of a DAQ Card for Analog/Digital conversion, a battery and a probe which contains the coils, ferromagnetic core and some circuits to calibrate and filter the signals; the measurement is carried out by putting the probe on the specimen: each measurement takes up less than 20 seconds to permit an average of the main parameters: it makes is possible to carry out very fast inspection. It is obvious that this kind of probe is very useful and free from any additional apparatus for lift-off adjustment as the eddy current evaluation [3]; furthermore the dimension of the probe facilitates the ease of handling as shown in Figure 6.

In this study 26 cast iron specimens with different hardness were prepared as the subjects. The measurements were carried out at 3 frequencies: 3 kHz, 6.8 kHz and 7.5 kHz. To show the reproducibility of the results we carried out a set of three measurements in three different days. The exitation voltage Vapplied in the measurements was 1.2 V to consider the reversible region in magnetization process.

Table 1 lists the Brinell hardness of the specimens used in this investigation. The hardness measured in advance varies from 140 HB to 270 HB.

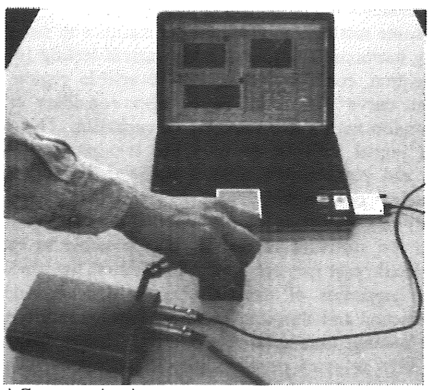
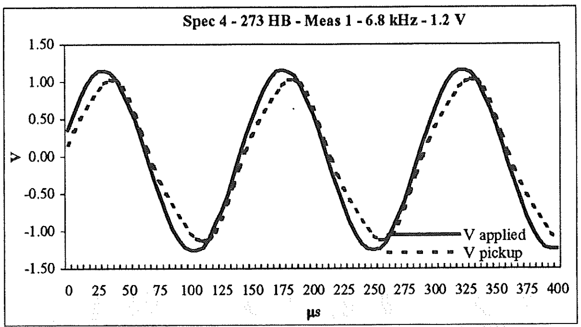


Figure 6: AC magnetization measurement system.

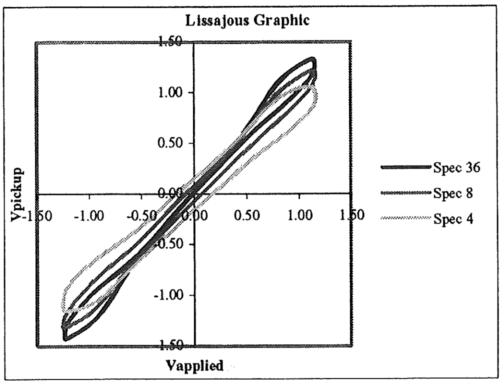
Table 1: ID and hardness of specimens.

Specimen ID	Hardness (HB)	Specimen ID	Hardness (HB)
21	139	12	169
36	142	17	171
18	144	16	178
20	145	22	179.5
27	146.5	25	182
24	150.5	14	189
47	151	51	193.5
26	152	6	196.5
23	154	9	201.5
15	160	8	202
35	161	7	208.5
13	164	5	266.5
19	168	4	273

4. Results and discussion



(a) Output waveforms



(b) Lissajous graphic

Figure 7: Output of the AC magnetization probe. (a) Waveform of exciting and detected voltages of the specimen ID 4. (b) Lissajous graphic of which the horizontal and vertical axes correspond to exciting and detected voltages, respectively.

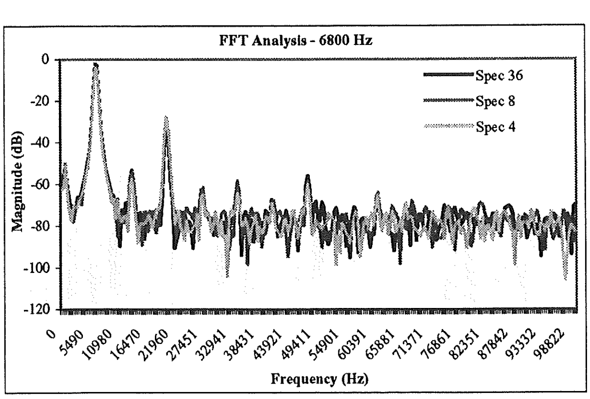
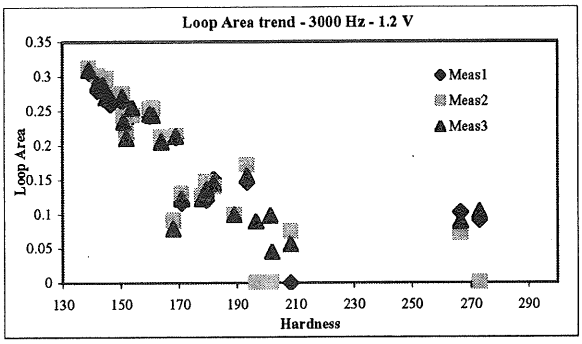


Figure 8: FFT analysis of the detected voltage for the specimens ID 36 (142 HB), 8 (202 HB) and 4 (273 HB) at 6800 Hz.

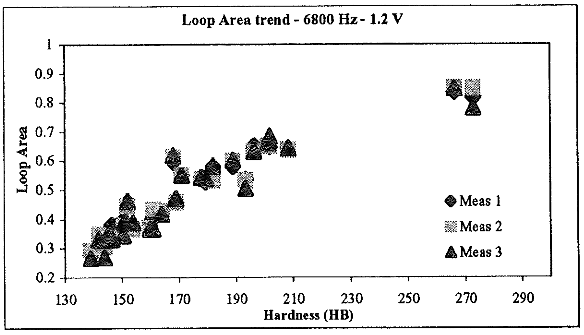
Figure 7 shows the output of the AC magnetization probe. In the Lissajous graphic of the waveforms, the results of specimens ID 36 (142 HB), 8 (202 HB) and 4 (273 HB) at the frequency 6800 Hz and exciting voltage 1.2 V are shown. The horizontal and vertical axes are represented by V applied and V pickup, respectively. Figure 8 plots the FFT analysis of the specimens of Figure 7 (b). This approach uses those measured data to characterize the structure of matrix.

4.1 Relation between Lissajous loop area and Hysteresis loss

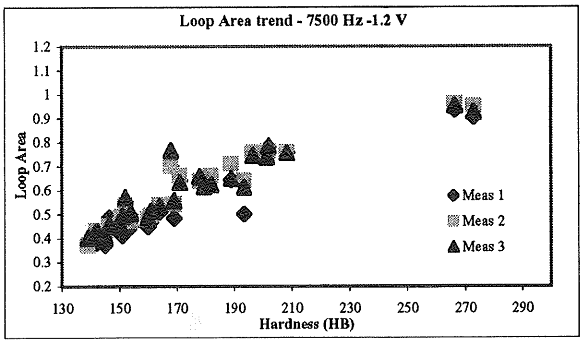
Taking the exciting voltage as the horizontal input and detected voltage as vertical input forms a Lissajous. An analogy is drawn between the magnetic hysteresis loop and the Lissajous from this experiment.



(a) 3000Hz



(b) 6800Hz



(c) 7500 Hz

Figure 9: Relation between the hardness and loop areas at 3000 Hz (a), 6800 Hz (b) and 7500 Hz (c), 1.2 V exciting voltage.

In magnetic hysteresis loop the horizontal axis is the field intensity H, and the vertical axis is the flux density B, corresponding to the exciting voltage and detected voltage respectively. The flux density is a measure of the intensity of the action of a magnetic field: there is the influence of the material and the magnetization state; while the detected voltage is a measure of the intensity of the action due to the exciting current. In this paper, the concepts of coercivity, residual, and hysteresis loss in magnetic hysteresis property, were used in AC voltage analysis as an equivalent value of AC magnetization. The equivalent values include an effect of eddy currents. The equivalent residual and coercivity are considered by "residual like" and "coercive force like", respectively. These equivalent parameters are defined as the zero-cross values of exciting and detected voltages, and the equivalent hysteresis loss *HL* is defined as the area of the Lissajous, as given by

$$HL = \sum_{V_E^{max}}^{V_E^{min}} \frac{1}{Z} V_D dV_E - \sum_{V_E^{min}}^{V_E^{max}} \frac{1}{Z} V_D dV_E \qquad (1)$$

where V_E [V] and V_D [V] denote the exciting and detected voltages, respectively; moreover Z is the impedance of probe.

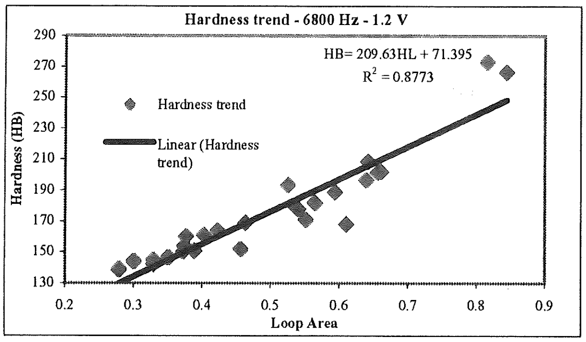
Figure 9 shows the trends of the loop area at 3000 Hz, 6800 Hz and 7500 Hz, 1.2 V exciting voltage. Three measurements were carried out in three different days to make sure the reproducibility. It is possible to observe the reproducibility of the results for both frequencies 6800 Hz and 7500 Hz in all measurements. In case of 3000 Hz, it is found that the different trend with the lack of reproducibility for values of hardness greater than 200 HB. The reason of these differences is that 3000 Hz is far to have the 3rd harmonic component intensity amplified and sensibility of probe is lower. Therefore we considered the results for 6800 Hz and 7500 Hz.

4.2 Regression curves of loop area

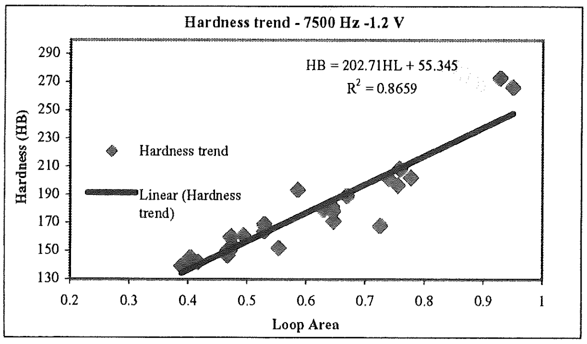
Regression curves based on the results of measurements in Figure 7 are formed from the following equation,

$$HB = m\,X + q \qquad (2)$$

where X is the calculated value (e.g., loop area, residual like, etc.); m and q are constants determined from the measurements. Since the detected voltage depends on frequency and exciting voltage, then constants m and q are determined by each measurement condition. HB is the value of hardness in HB. Using these regression curves it is possible to estimate the hardness depending on loop area. Figure 10 plots the trend of hardness depending on loop area (HL) at 6800 Hz and 7500 Hz. The figure was obtained from the average of the three measurements as shown in Figure 9 (b) and (c).



(a) 6800Hz



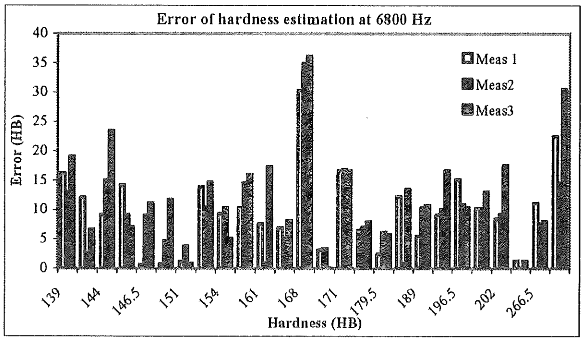
(b) 7500Hz

Figure 10: Trend of the hardness depending on loop area at 6800 Hz (a) and 7500 Hz (b), 1.2 V exciting voltage.

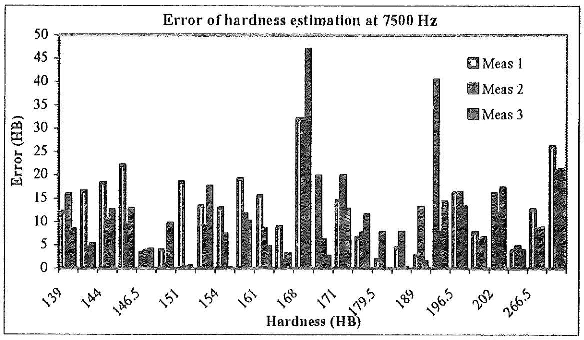
Table 2 lists the constants m and q of the regression curves for the two different frequencies 6800 Hz and 7500 Hz. The R-squared value, also well-known as the coefficient of determination or correlation, reveals how closely the estimated values for the trend line correspond to the measured data: in other words it is a value that supply a "goodness" of regression curve. A trend line is most reliable when its R-squared value is at or closed to 1.

Table 2: Constants of the regression curve with 1.2 V of exciting voltage

Frequency (Hz)	m	q	Average error (HB)	R^2
6800	209.63	71.39	±10.65	0.87
7500	202.71	55.34	±11.14	0.86

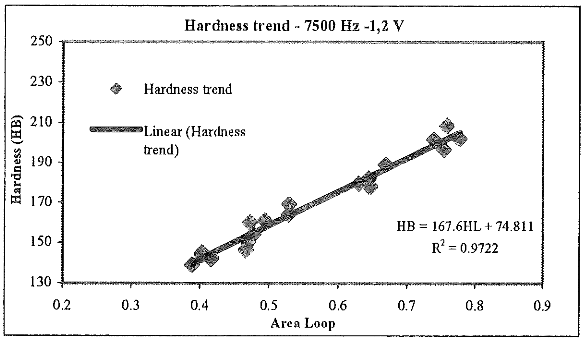


(a) 6800Hz

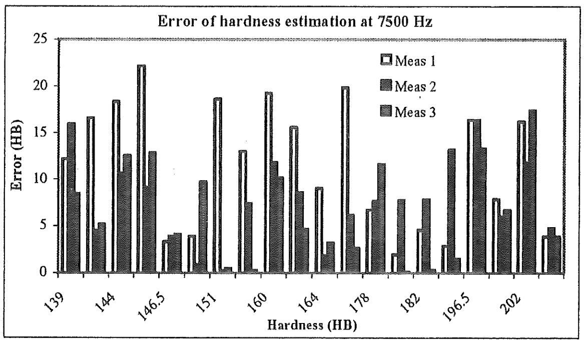


(b) 7500Hz

Figure 11: Histograms of errors of hardness estimation at 6800 Hz (a) and 7500 Hz (b). Error is defined as deviation from the regression curves in Figure 10.



(a) Loop area



(b) Error histogram

Figure 12: Hardness trend (a) and histogram of error of hardness estimation at 7500 Hz (b). Specimens with high average error were not considered.

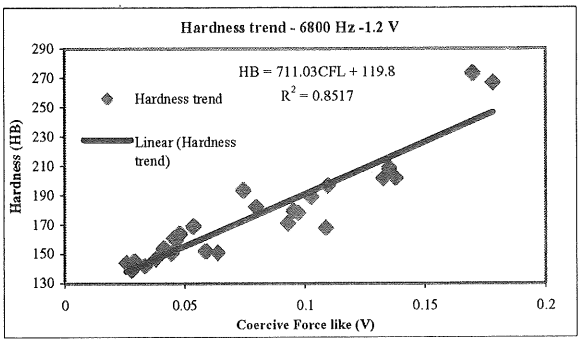
The average value of the error in the estimation of the hardness from the value of loop area is defined as deviation from the regression curve. Figure 11 summarizes the errors in the histograms for the three measurements: here error is defined as deviation from the regression curve. It can be observed that only one specimen of 168 HB in hardness significantly deviates for the linear fitting curve of experimental data.

Taking the consideration of the fact that Brinell hardness tests usually includes errors of about ±10 HB, the present method enables estimation of hardness in ductile cast irons with good accuracy. In this case the average error is ±10.65 HB and ±11.14 HB for investigation at 6800 Hz and 7500 Hz, respectively.

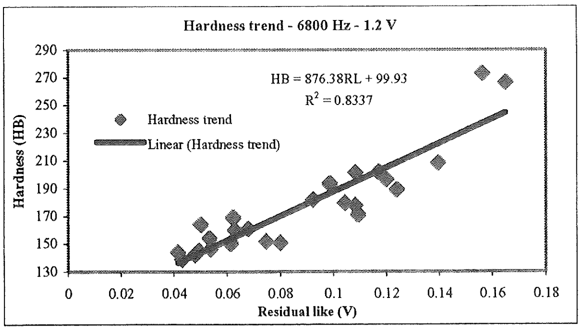
In case that some specimens with high average error are removed, it is possible to obtain R^2=0.97 and average error ±6.63 HB as shown in Figure 12.

4.3 Coercive force like, residual like and 3rd harmonic component intensity trend

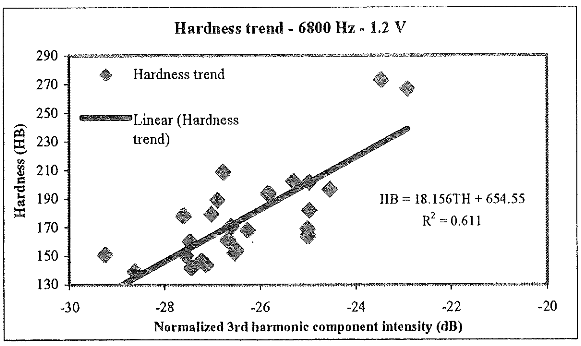
We analyzed also the trend of the equivalent coercivity and residual as "coercive force like " and "residual like", respectively defined as the zero-cross values of exciting and detected voltages; and the trend of the normalized 3rd harmonic component intensity, which is defined as the ratio of intensities of the 3rd harmonic to the fundamental components. These values are strongly correlated with the loop area showing the similar results to the discussion in the *Section 4.2*. The error is also similar.



(a) Coercive Force like



(b) Residual like

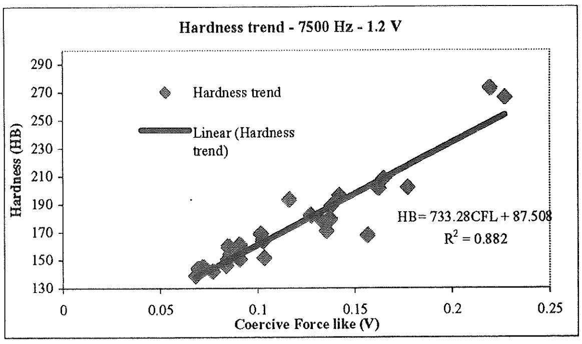


(c) Normalized 3rd harmonic component intensity

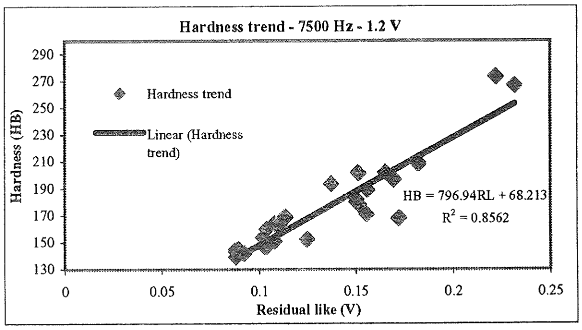
Figure 13: Trend of the hardness at 6800 Hz depending on "coercive force like" (a), "residual like" (b) and "normalized 3rd harmonic component intensity" (c).

Figure 13 shows the trend of the hardness depending on "coercive force like", "residual like" and "normalized 3rd harmonic component intensity" at the frequency of 6800 Hz and exciting voltage of 1.2 V. It can be observed that the trends of Figure 13 correspond to that of Figure 10 (a). It is possible to observe that the values increase as the hardness increases, as anticipated in the *Section 2*.

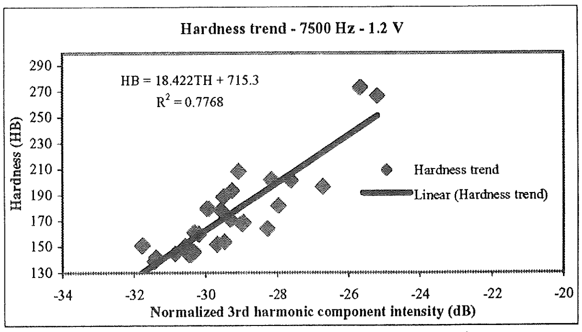
Figure 14 shows the trends for frequency of 7500 Hz, showing that the same trend as that in Figure 13. Table 3 summarizes the constants of the regression curve depending on frequency and on parameters, CFL, RL, and TH abbreviate is "coercive force like", "residual like", and "normalized 3rd harmonic component intensity", respectively. It can be seen that the average errors are in line with loop area trend average error.



(a) Coercive Force like



(b) Residual like



(c) Normalized 3rd harmonic component intensity

Figure 14: Trend of the hardness at 7500 Hz depending on "coercive force like" (a), "residual like" (b) and "normalized 3rd harmonic component intensity" (c).

Table 3: Constants of the regression curve with 1.2 V of exciting voltage for different parameters

Parameter	Frequency (Hz)	*m*	*q*	Averaging error (HB)	R^2
CFL	6800	711.03	119.8	±12.32	0.85
CFL	7500	733.28	87.51	±9.39	0.88
RL	6800	852.11	100.9	±15.73	0.80
RL	7500	796.94	68.21	±12.48	0.85
TH	6800	18.156	654.5	±23.09	0.61
TH	7500	18.422	715.3	±18.56	0.78

5. Summary

In this study, the AC magnetization method gives a novel material evaluation for cast irons. The particularity of this investigation is the amplified 3rd harmonic of the detected signals obtained in a range of frequencies between 5 kHz and 7 kHz. It could permit a high sensibility with low frequency and small dimension of probe.

A set of 26 specimens was prepared with different casting. The followings can be drawn from AC magnetization measurements of specimens:

1. The AC magnetization method enables us to assessing the hardness of the ductile cast irons independently on their chemical composition, thermal treatment and casting method.
2. The investigation presented in this paper provides a non-destructive evaluation of hardness of ductile cast irons with good accuracy in view of practical applications.
3. This probe used in this investigation makes it possible to carry out fast evaluation of hardness without lift-off noise like in eddy current testing.

Acknowledgments

The authors would like to thank the NDE Center of Japan Power Engineering and inspection Corporation (JAPEIC) for providing a probe. We acknowledge the specimens provided by Ube Steel Co., Ltd. We are also grateful to Professor Toshihiko Abe of Advanced System Evaluation Laboratory, Tohoku University for fruitful discussion and Takeshi Satoh of Institute of Fluid Science, Tohoku University for his technical assistance.

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