Journal of ELECTRICAL ENGINEERING, VOL 66. NO 7/s, 2015, 174-177

CORRELATION BETWEEN ULTRASONIC VELOCITY AND MAGNETIC ADAPTIVE TESTING IN FLAKE GRAPHITE CAST IRON

Gábor Vértesy* — Tetsuya Uchimoto — Toshiyuki Takagi** — Ivan Tomáš*****

A recently developed nondestructive method, called Magnetic Adaptive Testing was applied for investigation of flake graphite cast iron samples having various metallic matrices and graphite structures. MAT is typical by its low required magnetization of samples, because it is based on measurement of families of minor magnetic hysteresis loops. The flat samples were magnetized by an attached yoke and sensitive descriptors of their magnetic/structural state were obtained from evaluation of the measured data. Ultrasonic velocity measurements were performed and results of the non-destructive magnetic tests were compared with these data. A very good correlation was found between the magnetic descriptors and ultrasonic velocity.

Keywords: magnetic NDE, magnetic adaptive testing, flake graphite cast iron, ultrasonic velocity

1 INTRODUCTION

Cast iron is one of the most frequently used industrial construction materials. Low cost of production, good machinability, and excellent possibilities of shaping the details by casting attract an intense interest of industry. The cast irons are generally many-component alloys of iron with large content of carbon. The cast iron structure is classified by its metallic matrix composition (ferrite, pearlite, carbides, etc.) and by morphology of its graphite inclusion. The mechanical properties are fundamentally dependent both on the matrix composition and on the graphite shape (flaky, spheroidal, vermicular, etc.), size and density [1]. One of the types of cast iron - the flake graphite cast iron - is frequently used for mechanical components in bearings, brake shoes, etc. because of its high wear resistance and damping capacity. The flake graphite cast iron is an ideal material for automobile brake disks since it has excellent damping properties and thermal conductivity just because of the flaky graphite.

A nondestructive inspection of construction materials made of cast iron is highly desirable. Various non-destructive evaluation techniques have been examined so far, as *eg* alternating current potential drop [2], laser acoustic wave [3], ultrasonic back-scattering [4], or eddy currents [5]. Graphite and other structures composing the cast iron matrices may be evaluated using electromagnetic properties such as conductivity and permeability [6]. Magnetic measurements are also frequently used for characterization of changes in structure of ferromagnetic materials, because magnetization processes are closely related to microstructure of the materials. This fact also makes magnetic measurements an obvious candidate for non-destructive testing, for detection and characterization of any defects in materials and manufactured products made of such materials [7]. One of the most frequently used magnetic measurements is the detection of B-H curve. Structural non-magnetic properties of ferromagnetic materials have been non-destructively tested using traditional magnetic hysteresis measurement methods for a long time with fair success. A number of techniques have been suggested, developed and currently used in industry, see *eg* [8]. They are mostly based on detection of structural variations via the classical macroscopic parameters of hysteresis loops.

An alternative, more sensitive and more experimentally friendly approach to this topic was considered recently, based on magnetic *minor* loops measurement. The survey of this technique can be found in [9]. The method, called Magnetic Adaptive Testing (MAT) was presented, which introduced general magnetic descriptors to diverse variations in non-magnetic properties of ferromagnetic materials, optimally adapted to the just investigated property and material. MAT was successfully applied for characterization of material degradation in different specimens and it seems to be an effective tool *eg* for replacement of the destructive hardness and/or ductile-brittle transition temperature measurements.

In this work the direct correlation between MAT parameters and ultrasonic velocity in flake graphite cast iron is studied using samples with different graphite structures and matrices. Although ultrasonic velocity is not considered as the most important parameter of cast irons, it is a frequently measured quantity. The micro-structure of flake graphite cast iron is the most important parameter from point of view of cast iron properties. The correlation between graphite morphology and magnetic parameters has already been studied recently [10] based on the measurements performed on three as cast samples with different chemical compositions. It was also shown that ultrasonic velocity depends on the area fraction and length of graphite [6] on the same samples.

The purpose of the present work is to study the direct correlation between ultrasonic velocity and MAT parameters on three series of flake graphite cast iron samples, where apart from as cast samples two kinds of heat treatments (annealing to obtain a ferrite based matrix and nor-

---

* Institute of Technical Physics and Materials Science, Centre for Energy Research, Hungarian Academy of Sciences, H-1121 Budapest, Konkoly Thege Miklós út 29-33, Hungary, E-mail: vertesy.gabor@energia.mta.hu

**Institute of Fluid Science, Tohoku University, 2-1-1, Katahira, Aoba-ku, Sendai, 980-8577,Japan, uchimoto@ifs.tohoku.ac.jp

*** Center of Advanced and Innovative Technologies, VSB-TUO, 17.listopadu 15, 708 00 Ostrava-Poruba, Czech Republic

ISSN 1335-3632 © 2015 FEI STU

malization to obtain a pearlite-based matrix) were also performed.

2 SAMPLE PREPARATION

Three flake graphite cast iron materials with chemical compositions listed in Table 1 were prepared. Their carbon equivalent (CE) values were defined by:

$$CE = \text{mass}\,\%\text{C} + \frac{1}{3}(\text{mass}\,\%\text{Si} + \text{mass}\,\%\text{P})$$

and were controlled to produce various graphite shapes and sizes. These metals were designated as CE4.7, CE4.1 and CE3.7 based on their targeted CE values. Pig iron (4.09 %C, 0.89 %Si, 0.07 %Mn, 0.019 %P, 0.012 %S, 0.016 %Cr, 0.003 %Ti), ferrosilicon (Fe-75 %Si), electrolytic iron and electrolytic manganese were used as raw materials and were melted using a high frequency induction melting furnace at 1743 K. Ferrosilicon (Fe-75 %Si) was also used as an inoculant. The melts were poured into moulds made by the CO_2 gas process to produce columnar bars with length of 60 mm and diameter of 46 mm. Later each bar was cut into disks 12 mm thick. The disks were subjected to two kinds of heat treatments: annealing to obtain a ferrite based matrix and normalization to obtain a pearlite-based matrix. The disks intended for the heat treatments were kept in a furnace at 850ºC for one hour and then either cooled in the furnace for the annealing or cooled in air for the normalization. We thus produced 3 as-cast, 3 annealed and 3 normalized flake graphite cast iron materials with various matrices and graphite shapes as shown in Table 2. The Brinell hardness measuments indicated that the furnace-cooling and air-cooling treatments were successful in producing the ferritic and pearlitic matrices, respectively. The concrete graphite shapes are shown in [10].

Table 1. Chemical composition of the flake graphite cast iron samples (values in wt %)

Sample	Chemical composition						
	C	Si	Mn	P	S	Cr	Ti
CE4.7	3.77	2.78	0.78	0.025	0.015	0.029	0.015
CE4.1	3.36	2.15	0.69	0.018	0.010	0.014	0.011
CE3.7	3.13	1.66	0.72	0.017	0.020	0.038	0.010

3 MAGNETIC ADAPTIVE TESTING

MAT investigates a complex set of minor hysteresis loops (from a minimum amplitude of the magnetizing field, with increasing amplitude by regular steps) for each sample of the measured series. It follows from the theory of Preisach model of hysteresis [11], that such a set of experimental data contains complex information on hysteresis of the measured material. A specially designed Permeameter [12] with a magnetizing yoke was applied for measurement of families of minor loops of the magnetic circuit differential permeability. The flat samples were magnetized by an attached yoke. Size of the yoke was chosen to fit geometry of the samples: it was a C-shaped laminated Fe-Si transformer core with cross-section $S = 10 \times 5$ mm^2, total outside length 18 mm, and total outside height of the bow 22 mm. The magnetizing coil was wound on the bow of the yoke, with $N = 200$ turns and the pick-up coil was wound on one of the yoke legs with $n = 75$ turns. The magnetizing coil gets a triangular waveform current with step-wise increasing amplitudes and with a fixed slope magnitude in all the triangles. This produces a triangular time-variation of the effective field in the magnetizing circuit and a signal is induced in the pick-up coil. As long as the field sweeps linearly with time, the voltage signal in the pick-up coil is proportional to the differential permeability of the magnetic circuit. The Permeameter works under full control of a PC computer, which registers data-files for each measured family of the minor “permeability loops”.

Table 2. Schedules of the heat treatment

Base material	Heat treatment	Matrix
CE4.7	as-cast	mixed pearlite/ferrite
CE4.7	850ºC×1h, furnace-cooling	ferrite based
CE4.7	850ºC ×1h, air-cooling	pearlite-based
CE4.1	as-cast	mixed pearlite/ferrite
CE4.1	850ºC ×1h, furnace-cooling	ferrite based
CE4.1	850ºC ×1h, air-cooling	pearlite-based
CE3.7	as-cast	mixed pearlite/ferrite
CE3.7	850ºC ×1h, furnace-cooling	ferrite based
CE3.7	850ºC ×1h, air-cooling	pearlite-based

The experimental raw data are processed by an evaluation program, which divides the originally continuous signal of each measured sample into a family of individual permeability half-loops. The program filters experimental noise and interpolates the experimental data into a regular square grid of elements, $\mu_{ij} \equiv \mu(h_{ai},h_{bj})$, of a μ-matrix with a pre-selected field-step. The co-ordinates h_{ai}, h_{bj} of the elements represent the actual magnetic field value, h_{ai}, on the actual minor loop with amplitude h_{bj}. Each μ_{ij}-element represents one “MAT-descriptor” of the investigated material structure variation. The matrices are processed by another evaluation program, which divides values of their elements by corresponding element values of a chosen reference matrix (*ie* matrices standardization), and arranges each set of the mutually corresponding elements μ_{ij} of all the evaluated μ-matrices into a $\mu_{ij}(x)$-degradation function. Here x can be any independently measured parameter. In our case this is the conductivity, determined independently in the samples, as shown above. For details of the whole MAT procedure see [9]. Measurements were carried out on half disc shape samples with thickness of 12 mm and diameter of the discs 46 mm.

The samples are magnetized during the measurement by a magnetizing yoke, which is placed on the flat surface of the sample. This experimental arrangement means an open magnetic circuit, because some magnetic flux is always scattered at the air gap between the yoke and the sample. The exact value of the magnetic field *inside* the sample is not known/measured in the used experimental arrangement. Because of this, instead of the *magnetic field* (given in A/m), the value of the *magnetizing current* (given in mA) is used as h_{ai} and h_{bj} when the $\mu_{ij} \equiv \mu(h_{ai}, h_{bj})$ matrix elements are given.

4 ULTRASONIC VELOCITY

Both parallel surfaces of the disk specimen (12 mm thick) were polished using a milling attachment, and a 5 MHz broadband ultrasonic transducer was placed on one surface with coupling medium of machine oil. The ultrasonic velocity was evaluated by measuring the round-trip traveling time of the pulse between the two parallel surfaces using an oscilloscope. The longitudinal velocity was measured. The ultrasonic velocity of cast irons is discussed in [13]. According to this work the difference between longitudinal and transverse velocity (V_L and V_T) depends on the Poisson's ratio which is between 0.28 and 0.25 for two extremes of graphite shape. Therefore, V_L/V_T is almost the same and it does not make sense to measure the transverse velocity in addition to longitudinal velocity.

3 RESULTS AND DISCUSSION

The ultrasonic velocity of each our material was measured by the method described above. Fig. 1 shows its measured results for the as cast materials in relation to the graphite area fractions and the average length of the graphite flakes as they were evaluated using microphotograph binary images, see [10]. The ultrasonic velocity evidently depends on the area fraction and on the length of graphite. A model for the ultrasonic velocity of flake graphite cast iron was discussed in [14] based on the effective cross-section area fraction of the matrix, which is related to the total projected area of the graphite flakes in the ultrasound direction. Based on this model, the effective ultrasonic velocity in cast iron decreases with an increase of the amount of graphite and/or graphite length, because the main path of the sound leading through the metallic matrix "circumvents" volumes of the material filled up with the sound-damping graphite. This is in accordance with the relations shown in Fig. 1.

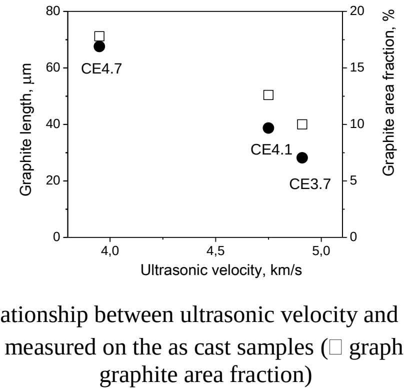

Fig. 1. Relationship between ultrasonic velocity and graphite parameters all measured on the as cast samples (□ graphite length, ♦ graphite area fraction)

The series of minor hysteresis loops were measured and MAT degradation functions of all the investigated samples were evaluated. MAT parameters were optimized for description of the studied dependences, *ie* of ultrasonic velocity. Optimization means that those μ_{ij}-degradation functions were chosen from the big data pool, which were the most sensitive with respect to the change of the independent parameter, and at the same time they were highly repeatable, and in such a way the most reliable.

The results for all samples are given in Fig. 2. Here each graph represents one type of the heat treatment (as-cast, air-cooling, furnace-cooling) and the graphs show how MAT descriptors depend on the ultrasonic velocity if the same heat treatment is applied for CE4.7, CE4.1 and CE3.7 samples. In this case MAT descriptors $1/\mu(h_a,h_b)$, with (h_a = -675 mA, h_b = 775 mA) coordinates were found as the best ones to describe the dependence of magnetic parameters as functions of ultrasonic velocity. In every case of Fig. 2 the MAT parameters are numerically normalized by the corresponding value of the sample within the same series, which has the lowest ultrasonic velocity.

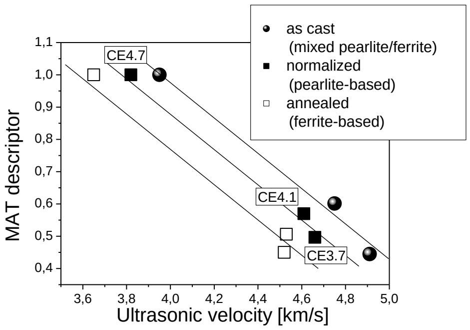

Fig. 2. The optimally chosen MAT descriptors for as cast, for air cooled and for furnace cooled samples

It is seen that a linear correlation with low scatter of points exists between magnetic characteristics and ultrasonic velocity. Considering the as cast samples, the different chemical compositions result in significantly different values of the same MAT descriptors. It means that by simultaneous measurement of ultrasonic velocity and of the MAT descriptors of as cast samples the actual chemical composition of each of the as cast samples can be estimated.

If air cooled (normalized, pearlite-based) and furnace cooled (annealed, ferrite-based) samples are considered, the value of ultrasonic velocity is rather close to each other for samples CE4.1 and CE3.7, (in the furnace cooled case in particular). However, some difference can be even better reflected in magnetic parameters. If proper magnetic parameters are chosen, even in this case an acceptable correlation and mutual differences can be found between MAT descriptors and ultrasonic velocity. This is illustrated in Fig. 3, where the optimally chosen magnetic parameters are given as functions of ultrasonic velocity separately for differently processed CE4.7, CE4.1 and CE3.7 materials. In this case MAT descriptors $1/\mu\,(h_a,h_b)$, with (h_a=570 mA, h_b=750 mA) coordinates were found as the best ones to describe the dependence of magnetic parameters as functions of ultrasonic velocity. In this figure – for the better comparison – the MAT descriptors are *not* numerically normalized.

The influence of heat treatment is reflected here very well on magnetic parameters. Note that in this figure *different* $\mu(h_a,h_b)$ MAT descriptors are given than in Fig. 2. This behavior shows also very well the *multi-parametric character* of Magnetic Adaptive Testing and its advantage: different sets of magnetic descriptors correlate differently with the independent parameter, which can be frequently utilized with great benefit.

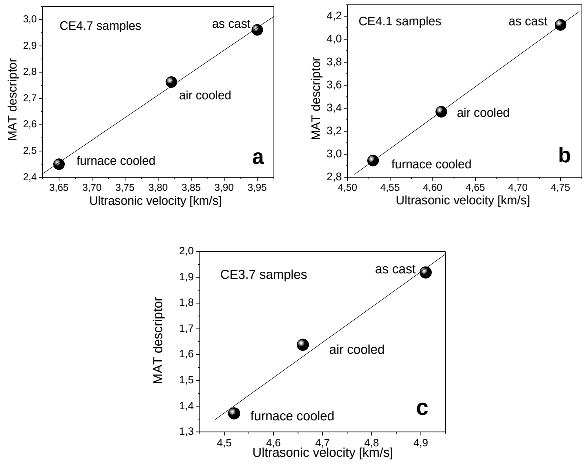

Fig. 3. The optimally chosen $\mu(h_a,h_b)$ MAT descriptors for sample CE4.7 (a), for sample CE4.1 (b) and for sample CE3.7 (c).

4 CONCLUSIONS

The method Magnetic Adaptive Testing, which is based on nondestructive, systematic measurement of minor magnetic hysteresis loops was applied for three flake graphite cast iron materials with different chemical compositions (*ie* different graphite morphology) and different structures of metallic matrices. MAT was shown to be a useful tool for finding correlation between the chosen nondestructively measured magnetic parameters and the ultrasonic velocity. Linear correlations with very small scatter of points were found between the optimally chosen MAT degradation functions and ultrasonic velocity both if the same chemical composition with different heat treatment and also if the same heat treatment on different chemical compositions were considered.

Acknowledgements

This work was partly supported by the JSPS Core-to-Core Program, „Advanced Research Networks” (International research core on smart layered materials and structures for energy saving), by Hungarian Scientific Research Fund (project K 111662) and by the Researcher Exchange Program between the Japan Society for Promotion of Science and Hungarian Academy of Sciences.

REFERENCES

[1] C.F. WALTON, T.J. OPAR (Eds.), Iron casting handbook, Iron casting society, Inc., New York, 1981

[2] J.R. BOWLER, Y. HUANG, H. SUN, J. BROWN, N. BOWLER, Alternating current potential-drop measurement of the depth of case hardening in steel rods, Measurement Science and Technology 19 (2008) 075204.

[3] D. SCHNEIDER, R. HOFMANN, T. SCHWARZ, T. GROSSER, E. HENSEL, Evaluating surface hardened steels by laser-acoustics Surface and Coatings Technology 206 (2012) 2079.

[4] H. WILLEMS, Review of Progress in Quantitative Nondestructive Evaluation 10B (1991) 1707.

[5] S. KONOPLYUK, T. ABE, T. UCHIMOTO, T. TAKAGI, M. KUROSAWA, Characterization of ductile cast iron by eddy current method, NDT&E International, 38 (2005) 623

[6] T. UCHIMOTO, T. TAKAGI, T. ABE, Electromagnetic Nondestructive evaluation of graphite structures in flake graphite cast iron, MATERIALS TRANSACTIONS, 51 (2010) pp. 1114-1119

[7] D.C. JILES, *Magnetic methods in nondestructive testing*, K.H.J.Buschow et al., Ed., Encyclopedia of Materials Science and Technology, Elsevier Press, Oxford, (2001), 6021.

[8] D.C. JILES, Review of magnetic methods for nondestructive evaluation *NDT International*, 21 (1988), 311-319.

[9] I. TOMÁŠ, G. VÉRTESY, Magnetic Adaptive Testing, In: Nondestructive Testing Methods and New Applications, M.Omar (Ed.), ISBN: 978-953-51-0108-6, (2012), InTech: http://www.intechopen.com/articles/show/title/magnetic-adaptive-testing

[10] G. VÉRTESY, T. UCHIMOTO, T. TAKAGI, I. TOMÁŠ, Flake graphite cast iron investigated by a magnetic method, IEEE Trans. Magn, Vol. 50. (2014) 6200404

[11] I.D. MAYERGOYZ, Mathematical models of hysteresis, Springer-Verlag, New York, 1991

[12] I. TOMÁŠ, O.PEREVERTOV., in: JSAEM Studies in Applied Electromagnetics and Mechanics 9, ed. T. Takagi and M. Ueasaka, (IOS Press, Amsterdam, 2001), 5-15

[13] D.N. COLLINS, W. ALCHEIKH, Ultrasonic non-destructive evaluation of the matrix structure and the graphite shape in cast iron, J. Materials Processing Technology, 55 (1995) 85-90

[14] T. ABE, K. IKAWA, IMONO 58 (1986) 479

Received 30 November 2015

Gábor Vértesy (DSc, PhD), born in Budapest, Hungary, in 1951. Graduated from Eötvös Loránd University, Budapest, in 1974 and received his PhD degree from Hungarian Academy of Sciences in 1995. At present he is scientific advisor of Photonics Department of the Institute for Technical Physics and Materials Science of Hungarian Academy of Sciences. His main field is study of ferromagnetic materials and novel nondestructive electromagnetic testing methods for characterization of structural industrial materials.

Tetsuya Uchimoto, (Dr Eng) born in Kanagawa, Japan in 1970. He received his BEng, MEng, and DEng degrees in nuclear engineering from the University of Tokyo, Japan, in 1993, 1995, and 1998, respectively. He is an Associate Professor of Institute of Fluid Science, Tohoku University, Sendai, Japan. His research interests include evaluation of degradation of structural materials, electromagnetic nondestructive evaluation of cast irons by eddy currents, and novel sensor development

Toshiyuki Takagi (Dr Eng), born in Nagoya, Japan, in 1954. He received his BEng, MEng, and DEng degrees in nuclear engineering from the University of Tokyo, Japan, in 1977, 1979, and 1982, respectively. Since 1998 has been Professor, at the Institute of Fluid Science, Tohoku University. His current research interests include nondestructive evaluation of materials, diamond and carbon coatings and their application, and adaptive structural systems using shape memory alloys.

Ivan Tomáš (RNDr, PhD), born in Prague, Czech Republic, in 1943. Graduated from the Faculty of Mathematics and Physics at Charles University, Prague, in 1967, and received his PhD degree from the Czechoslovak Academy of Sciences in 1973. Presently he is with Institute of Physics, ASCR, Prague and at the Center of Advanced and Innovative Technologies, VSB-TUO, Ostrava. His main field is ferromagnetism of solids, with a strong interest in magnetic testing of variation and degradation of ferromagnetic industrial materials.