NDT&E International 74 (2015) 8–14

Contents lists available at ScienceDirect

NDT&E International

journal homepage: www.elsevier.com/locate/ndteint

Nondestructive characterization of flake graphite cast iron by magnetic adaptive testing

Gábor Vértesy [a,*], Tetsuya Uchimoto [b], Toshiyuki Takagi [b], Ivan Tomáš [c], Hidehiko Kage [d]

[a] *Hungarian Academy of Sciences, Institute of Technical Physics and Materials Science, Budapest, Hungary*
[b] *Institute of Fluid Science, Tohoku University, Sendai, Japan*
[c] *Center of Advanced and Innovative Technologies, VSB-TUO, Ostrava, Czech Republic*
[d] *Kusaka Rare Metal Co., Ltd. Tokyo, Japan*

ARTICLE INFO

Article history:
Received 2 January 2015
Received in revised form
15 April 2015
Accepted 17 April 2015
Available online 25 April 2015

Keywords:
Cast iron
Magnetic hysteresis
Magnetic adaptive testing
Nondestructive testing

ABSTRACT

Three series of flake graphite cast iron samples having different chemical compositions and different heat treatments within each series were investigated by the method of magnetic adaptive testing. The flat samples were magnetized by an attached yoke, and sensitive descriptors were obtained from the proper evaluation, based on the measurements of series of magnetic minor hysteresis loops, without magnetic saturation of the samples. Results of the non-destructive magnetic tests were compared with the destructive mechanical measurements of Brinell hardness and linear correlation was found between them in all cases, where the influence of chemical composition and influence of heat treatment were considered.

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.

The standard method of determining mechanical properties is the hardness test, in which indentations are made from the surface to the core. This method is destructive and time consuming. Because of this an easy nondestructive check-up of properties of the cast iron is highly desired. Various non-destructive evaluation techniques have been examined so far as an alternative method; alternating current potential drop [2], laser acoustic wave [3], ultrasonic back-scattering [4], eddy currents [5–7], photothermal radiometric radiometry [8].

Each technique gives indications of a good correlation between a measured physical parameter and hardness.

Magnetic measurements are also frequently used for characterization of changes in ferromagnetic materials, because magnetization processes are closely related to their microstructure. This makes the magnetic approach an obvious candidate for non-destructive testing, for detection and characterization of any defects in materials and in products made of such materials see e.g. [9]. The well known Barkhausen noise effect can also be used for estimation of hardness in cast iron [10–13]. The so-called 3MA-approach (micromagnetic, multiple-parameter, microstructure, and stress analysis) was developed [14] in the last decade. This approach combines the information resulting from the performance of different micromagnetic techniques (magnetic Barkhausen noise, incremental permeability, harmonic analysis of the magnetic tangential field and eddy current testing used at 3 different frequencies). By using the 3MA-method a nondestructive hardness measurement is also possible [15].

A frequently and successfully used magnetic method is the measurement of hysteresis loops. This method is mostly based on detection of structural variations via the classical parameters of *major* hysteresis loops. Structural non-magnetic properties of ferromagnetic materials have been non-destructively tested using traditional hysteresis methods since long time with fair success. A number of techniques have been suggested, developed and currently used in industry, for a review see e.g. [16]. Hardening of

---

[*] Corresponding author.

http://dx.doi.org/10.1016/j.ndteint.2015.04.004
0963-8695/

steel is measured by detection of B–H loops as published is some recent works [17,18]. By applying this method, problems of nondestructive testing controlling the structure of casting products were analyzed, too. Coercive force, residual magnetization and saturation magnetization for white, gray, malleable and high-strength cast irons at different structure of metallic matrices were measured. It was found that measurement of the coercively sensitive magnetic parameter guarantees the quantitative control of hardness of casts without surface cleaning [19,20].

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 [21]. 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 e.g. for replacement of the destructive hardness and/or ductile-brittle transition temperature measurements.

In our previous works [22–24] magnetic characteristic parameters of a system of minor loops, measured on a series of ductile cast iron samples, were analyzed, and their sensitivity was evaluated. The flat samples were magnetized by an attached yoke and sensitive parameters were obtained from the series of minor loops, without magnetic saturation of the samples, which characterize well the samples' structure. In a recent work [25] MAT was applied for three flake graphite cast iron materials with different chemical compositions and different matrix and flake graphite properties. Metallographic examination of the matrix and the graphite structures was performed and results of the nondestructive magnetic tests were compared with these data. A very good correlation was found between the magnetic descriptors and the graphite morphology. MAT was shown to be a useful tool for finding correlation between the chosen nondestructively measured magnetic parameters and the graphite morphology. Linear correlations with very small scatter of points were found between the optimally chosen MAT degradation functions and both the graphite length and the graphite area of the as-cast samples.

The purpose of the present work is to continue these measurements on three series of flake graphite cast iron samples, to investigate the influence of both graphite morphology structure and of matrices on mechanical and magnetic hardening, and to find correlation between nondestructively measured magnetic parameters and destructively determined Brinell hardness. We will also discuss the advantages of magnetic adaptive testing compared with other existing nondestructive magnetic methods.

2. Samples

Three flake graphite cast iron materials with chemical compositions listed in Table 1 were prepared.

Their carbon equivalent (CE) values were defined by:

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

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 the columnar bars with a length of 60 mm and a diameter of 46 mm. Later each bar was cut into disks 10 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 850 °C 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.

After grinding the specimen surfaces, their Brinell hardness HB (HBW 10/3000) was measured and it is also listed in Table 2. These hardness values indicate that the furnace-cooling and air-cooling treatments were successful in producing the ferritic and pearlitic matrices, respectively.

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

Sample	Chemical composition							CE (%)
	C	Si	Mn	P	S	Cr	Ti	
CE4.7	3.77	2.78	0.78	0.025	0.015	0.029	0.015	4.71
CE4.1	3.36	2.15	0.69	0.018	0.010	0.014	0.011	4.08
CE3.7	3.13	1.66	0.72	0.017	0.020	0.038	0.010	3.69

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 [26], that such a set of experimental data contains complex information on hysteresis of the measured material.

The essential difference between material testing by the traditional hysteresis- and by the MAT-approach is shown in Fig. 1 schematically. The left hand part of the figure represents the traditional measurement of the *single major* (saturation) hysteresis loop. The major loop is measured for each of the investigated samples and the material degradation can be described through variation of values of any *of the few major loop parameters*, e.g. H_C, B_R,… as functions of an independent degradation variable, ε. The right hand part of the figure depicts schematically volume of the measured data for MAT. The large family of minor hysteresis loops is measured for each of the investigated samples and the material degradation can be then described through variation of values *of any of the point (and/or slope) on any of the minor loops*, i.e. $B(F_i, A_j)$ (and/or $\mu(F_i, A_j)$), as functions of any independent degradation variable, ε. In the present case the Brinell hardness is the independent parameter, i.e. *HBW* values will be used later as ε.

Table 2
Schedules of the heat treatment and the Brinell hardness (HBW).

Base material	Heat treatment	HBW
CE4.7	As-cast	100
CE4.7	850 °C × 1 h, furnace-cooling	89
CE4.7	850 °C × 1 h, air-cooling	130
CE4.1	As-cast	183
CE4.1	850 °C × 1 h, furnace-cooling	110
CE4.1	850 °C × 1 h, air-cooling	209
CE3.7	As-cast	207
CE3.7	850 °C × 1 h, furnace-cooling	130
CE3.7	850 °C × 1 h, air-cooling	221