THE USE OF MAGNETIC AND ULTRASONIC STRUCTUROSCOPY FOR THE PROCESS CONTROL OF AUSTEMPERED IRONS

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Abstract

This paper summarizes the most important results of research dealing with the use of magnetic spot-pole method and measurement of ultrasonic wave velocity for process control of castings made of austempered ductile, grey and vermicular-graphite irons. It describes the most important dependencies of measured physical quantities on the specific structure of these materials, especially the content of retained austenite. Suggests other possible developments of this control methodology.

Keywords: magnetic structuroscopy, ultrasonic structuroscopy, austempered irons

1. INTRODUCTION

The Austempered Ductile Iron (ADI), Austempered Grey Iron (AGI) and newly the Austempered Vermicular-Graphite Iron (AVGI) represent the most progressive group of grafitic irons with reference to mechanical properties. However, these properties depend on accurate observance of default structure, chemical composition and conditions of the austempering. Austempered castings are mostly used in automotive industry for moving parts and safety critical items. [1], [2], [4] The non-destructive testing can be used as the 100% inspection of the heat treatment – that provides constant production quality and may help with the wider implementation of this promising material into the production. So far, the known inspection procedures are based on measuring of the natural frequency, attenuation, or eddy current - see [11] to [14]. This paper deals with the the magnetic spot-pole method and common ultrasonic testing. [5], [6], [10], [15]

2. NDT STRUCTUROSCOPY

Properties of iron castings depend on the properties of the matrix as well as on the presence of graphite. Both can be examined without destruction. As mentioned, for the inspection of austempered castings were selected two methods – measurement of the ultrasonic velocity (of longitudinal waves – c_L [m/s] and the measurement of the intensity of the residual magnetic field - Hr [A/m].

2.1 The use of magnetic and ultrasonic structuroscopy for inspection of iron castings

In case of ultrasound the passage of the beam trough the iron depends primarily on the shape, size and distribution of the graphite particles. The less compact particles of graphite, the greater is the attenuation of ultrasonic beam at the interface of graphite and the matrix. The same effect as graphite, have components of matrix with different acoustic impedance. However, in the as-cast state, this effect is less pronounced than the effect of graphite. With increasing attenuation decreases the ultrasonic speed in the material. The ultrasonic speed can be easily used to determine the morphology of graphite (in as-cast state), or for the matrix inspection (in heat treated state). Because the ultrasonic speed is a function of the modulus of elasticity, density and Poisson's ratio, can be at a known velocity of longitudinal and transverse waves determined some elastic constants (such as tensile modulus, shear modulus). More often is (directly on components) measured the initial elastic modulus E_0 [MPa], which is modulus at initial load (in case of acoustic wave it´s in the range of

Pascals). It is instructive value, expressing the rigidity of the material, but there are also mathematical models characterizing graphite shape using E_0. (The E_0 is also a function of c_L.) [6], [7], [8]

Magnetic structuroscopic methods exploit the relationship between structural parameters and magnetic properties. The main characteristics of ferromagnetic materials are areas with identically oriented atoms – domains. These domains represent sub-grains of crystalline structure. After the polarization by external magnetic field H_0 [A/m], the domains with identic or similar orientation are growing (by shift of the Bloch zones) or changing the polarization through Barkhausen effect. When the external field passes, not every domain returns into the initial state. Then origins a residual polarization Ir [T]. A place which was magnetized has its own magnetic field with the intensity of Hr [A/m]. This field is spot-like. Reversible changes of the domain orientation are disabled by atoms bonded in molecules, atomic stress and lattice defects. Therefore components containing carbides, martensite, displacements or grain boundaries have a high value of residual polarization Ir. [5], [8], [10]

$$H_r = H_0 - \frac{N \cdot I_r}{\mu} \left[A \cdot m^{-1} \right] \quad (1)$$

Where: *Hr*…intensity of residual magnetic field [A/m], H_0…intensity of external magnetic field [A/m], *N*…demagnetizing factor [-], *Ir*…residual polarization [T], μ…magnetic permeability [-].

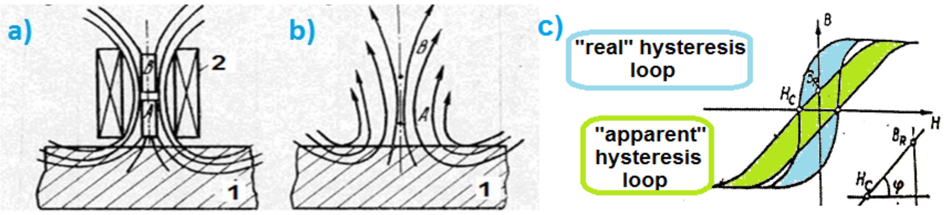

Fig. 1 Magnetic spot - pole method; a) magnetizing; b) measurement; c) linearization of the hysteresis loop in the second quadrant; A, B – Hall sensors; 1 – ferromagnetic material; 2 – magnetizing coil. [5]

Because the controlled parts have often a huge demagnetizing factor N, the relation between the residual induction Br and coercivity Hc is linear (see **Fig. 1c**; the linearizing of the hysteresis loop in the second quadrant). Hc often reacts sensitively on mechanical properties, e.g. strength, hardness etc. This principle is used by a magnetic spot-pole method (**Fig. 1 a,b**). A magnetic „spot-pole“ is created in the surface of tested material by a magnetizing coil inside a probe. While the current pulse in the coil passes, the residual magnetic field Hr in the surface is measured by sensors. These sensors (mostly Hall sensors) are differentially connected to measure a gradient of tangential or normal part of the field. [9], [15]

As mentioned, the value of Hr is related with the structure/matrix of the ferromagnetic material. That provides measurement of hardness, strength or the hardened depth. It was found, that using repeated magnetizing is possible to determine structural components (pearlite, sorbite, martensite). It´s possible to detect and to measure a depth of decarburization. Correlation between the monitored quantity and measured intensity of residual magnetic field must be experimentally traced and the device then must be calibrated. The method was successfully applied on steel and cast iron, the most common use is for interoperating control of castings (through the HB or Rm). Results of measurement may be influenced by the shape of the sample (demagnetizing factor) and the type of material (steel/iron). Therefore it is necessary to calculate with marginal effect, effect of thin walls or shielding effect (diamagnetic graphite) to refine results. There´s also a significant influence of temperature (Hall sensors are made of semiconductor materials). It´s necessary to measure shot - blasted surface without residual ferromagnetic oxides (huge influence on Hr). [5], [8], [16] Both methods (magnetic and ultrasonic) are already known in the field of NDT inspection of steel products and iron castings - see e.g. [5] to [9]. Dependencies between structural parameters and properties of these materials have been researched and successfully applied. In case of austempered iron with unusual structure (high content of paramagnetic austenite, considerable influence of graphite morphology) non-monotonic dependencies are expected and therefore they must be at first carefully observed and assessed. That´s why are used two kinds of structuroscopy with different sensitivity to structural influences.

2.2 Experiments – short review

For experiments was created a set of reference samples of cast iron with lamellar, spheroidal and vermicular graphite (chemical composition see in **Table 1**). Heat treatment was carried out under the following conditions: austenitizing at 900°C/30 or 90 minutes, austempering in molten salt at temperatures 240, 310 and 400°C for 2, 10, 30 and 60 minutes, final cooling in air. This has provided the structure of the lower, upper and transition (middle) ausferrite.

Table 1 Chemical composition of used irons - **AGI**, **AVGI** and **ADI**.

C [%]	Si [%]	Mn [%]	P [%]	S [%]	Cu [%]	Ni [%]	Mo [%]	Cr [%]	Mg [%]
3.15	2.24	0.19	0.02	0.016	0.02	0.01	-	-	-
3.62	3.5	0.18	0.024	0.015	0.21	-	0.35	0.04	0.014
3.3	2.45	0.25	0.02	0.015	0.04	-	-	-	0.046

Experiments were carried out according to the following schedule:

- measurements on a wide set of samples ADI / AGI with matrix of lower and upper ausferite by use of conventional methods - obtaining the necessary data of physical and mechanical properties of the material
- measurements using NDT structuroscopy - obtaining of necessary parameters of structure
- interpretation of results, data analysis
- dependencies between structural parameters and physical quantities - specification of the work setting of NDT methods for measurements on a wide set of austempered castings
- calibration of instruments and testing of procedures in real part production

2.3 Major dependencies between austempered structure and acoustic properties

As mentioned, the main influence in as-cast state is given by the graphite. It can be used for the initial inspection. After austempering to the influence of graphite adds even more pronounced influence of microstructure. The ultrasonic speed decreases up to hundreds of m/s thanks to the presence of ausferrite. This is due to a difference of acoustic impedance of Fe gamma and Fe alpha on their mutual interface. The structure of ausferrite represents a huge amount of barriers to the spread of ultrasonic beam. The more these barriers, the speed is lower. The lowest values thus achieves the fine and acicular structure of lower ausferrite and a top speed within a given range has the coarse structure of upper ausferrite (see **Fig. 2**). For the identification of austempered matrix can be used same the total value of c_L as the differential between the as-cast and heat treated state - dc_{LTZ}, which is maybe more conclusive. Of course, speed values can be connected with the required parameters of the structure, such as content of stabilized austenite.

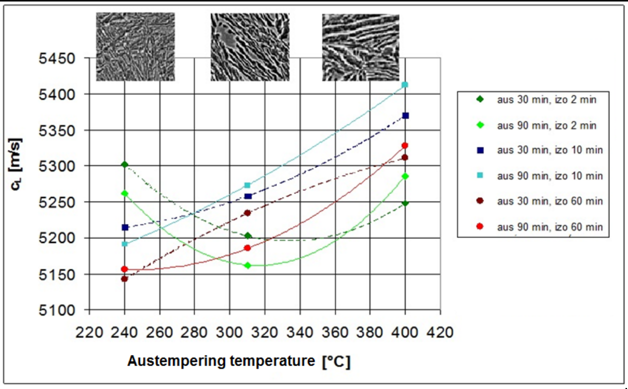	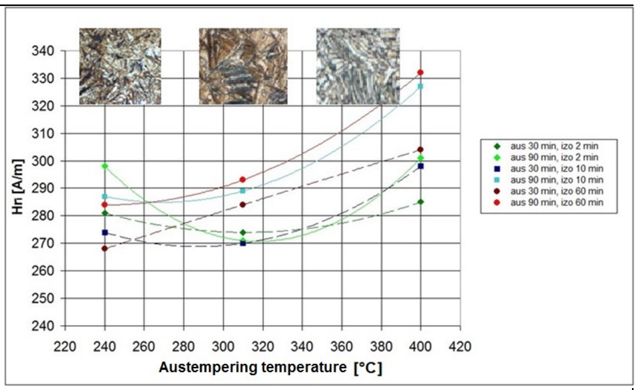
Fig. 2 The dependence of c_L on HT conditions (AVGI)	**Fig. 3** The dependence of H_r on HT conditions (AVGI)

2.4 Major dependencies between austempered structure and magnetic properties

Comparing the results of magnetic measurements shows that while the iron in as-cast state influences the value of the residual magnetization mostly by its mechanical properties (Hr increases linearly with the hardness and strength), after the austempering process the main influence on Hr is given by the content of paramagnetic stabilized austenite. This influence is dominant and covers all the other influences (such as graphite, mechanical properties, etc.). The value of residual magnetization compared to as-cast state is multiple. It is caused by the specific structure, which is similar to the composite of ferromagnetic ferrite needles/laths with a binder from paramagnetic austenite. So, the structure represents thin layers of ferromagnetic material, separated by non-ferromagnetic insulation (so the influence of the wall thickness along with the shielding effect are summarized - the same effect have been observed in case of graphite – see [9]). The fine structure of the matrix after austempering also presents a number of obstacles to the movement of the magnetic domains (the “magnetic hardness” of the material is increasing). The value of the residual magnetization increases with increasing content of stabilized austenite. This dependence is nonlinear (see **Fig. 3**).

To check the effect of the HT can be reliably used the total value of the residual magnetization Hr as well as the difference between the first and second magnetization from the virgin state - dHr. As seen from the **Table 2**, different ranges of values corresponding to individual structures are relatively smoothly linked.

Table 2 Table of dHr values in dependence on matrix of AGI, AVGI and ADI

Microstructure of the matrix - AGI	**dHr** [A/m]	**Microstructure of the matrix - AVGI**	**dHr** [A/m]	**Microstructure of the matrix - ADI**	**dHr** [A/m]
pearlite+ferrite	12	ferrite	9	ferrite+pearlite	11
martensite, lower ausferrite	31-33	martensite, lower ausferrite	29-32	martensite, lower ausferrite	32-34
lower ausferrite	34-38	lower ausferrite	33-39	lower ausferrite	35-40
transitional ausferrite	42-48	transitional ausferrite	45-50	transitional ausferrite	42-50
upper ausferrite	50-60	upper ausferrite	52-60	upper ausferrite	51-60

Similarly, the value of Hr/dHr can be reliably combined eg. with austenite content or can successfully used for detection and measurement of undesirable decarburization. Due to the opposite effects is not very reliable to use values of the residual magnetization for determination the mechanical properties (esp. strength) as in the case of as-cast iron. For determination of mechanical properties will be necessary to establish multiparametric dependencies based on both magnetic and ultrasonic parameters with much more frequent data file.

CONCLUSIONS

On the base of dependencies was set up an inspection procedure - see **Fig. 5**.

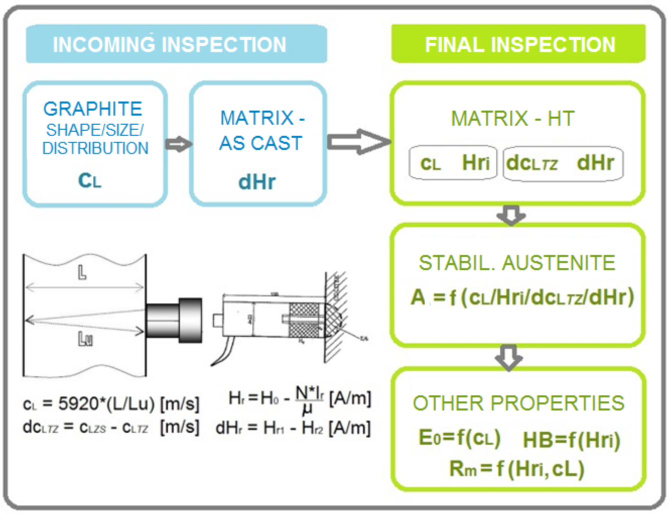

Fig. 5 Scheme of the inspection using ultrasonic speed and residual magnetization

A key for incoming inspection is the measurement of the ultrasonic speed c_L to exclude castings with improper graphite. The matrix inspection should follow, using the differential of residual magnetization dHr. After the heat treatment is necessary to identify the matrix using the Hr or dHr as well. To eliminate failure of the inspection is also recommended to measure ultrasonic speed c_L or the speed´s differential dc_{LTZ}. Both groups of values are for identification matrix sufficiently conclusive. According to the specific requirements the measured values can then be converted to known parameters of the structure, such as amount of stabilized austenite or mechanical properties (hardness, strength, initial elastic modulus).

It should be noted that the dependencies were obtained using laboratory specimens under optimal conditions (esp. excluding the influence of shape or wall thickness). At present time the verification of dependencies is running together with the implementation of inspection procedures in the production of specific parts of austempered irons (ADI and AGI). Since it is generally thin-walled castings, and circular shape, it is necessary to correct dependencies due to the influence of wall thickness and the radius of curvature. In further work will be necessary to extend existing values with more austempering temperatures and dwells.

Reliable and affordable non-destructive diagnostics will support the reproducibility of austempered castings and thus awaken interest of primarily European potential manufacturers of these excellent materials. Especially the austempered iron with vermicular graphite has a considerable potential. The intended application is for cylinder liners and brake discs.

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