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

ANDRSOVA Zuzana [1], VOLESKY Lukas [1], SKRBEK Bretislav [1], SEJNOHOVA Ivana [2]

[1]*Institute for Nanomaterials, Advanced Technologies and Innovations, Technical University of Liberec, Liberec, Czech Republic, EU,*
zuzana.andrsova1@tul.cz, lukas.volesky@tul.cz, bretislav.skrbek@tul.cz
[2] *RESL, s.r.o, Liberec, Czech Republic, EU, ivana.sejnohova@obrobna.cz*

Abstract

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

Keywords: Magnetic structuroscopy, ultrasonic structuroscopy, austempered irons

1. INTRODUCTION

Austempered ductile iron (ADI), austempered grey iron (AGI) and more recently austempered vermicular-graphite iron (AVGI) represent the most progressive group of graphitic irons with reference to mechanical properties. However, these properties depend on accurate observance of the default structure, chemical composition and conditions of the austempering. Austempered castings are mostly used in the automotive industry for moving parts and critical safety items. [1], [2], [3] Non-destructive testing can be used for a thorough inspection of heat treatment in order to provide constant production quality and help with the wider use of this promising material in production. The currently known inspection procedures are based on measuring the natural frequency, attenuation, or eddy current - see [4] to [7]. This paper deals with the magnetic spot-pole method and also common ultrasonic testing. [8], [9], [10]

2. NDT STRUCTUROSCOPY

The properties of iron castings depend on the properties of the matrix as well as on the presence of graphite. Both can be examined in a non-destructive manner. As mentioned above, two methods were selected for the inspection of austempered castings - measurement of ultrasonic velocity (of longitudinal waves - c_L [m/s] and the measurement of intensity of the residual magnetic field - H_r [A/m].

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

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

an acoustic wave it is in the range of Pascals. It is an instructive value, expressing the rigidity of the material, however, mathematical models can also be used to characterize graphite shape using E_0, which is also a function of c_L. [11], [12]

Magnetic structuroscopic methods exploit the relationship between structural parameters and magnetic properties. The main characteristics of ferromagnetic materials are areas with identically oriented atoms - known as domains. These domains represent sub-grains of crystalline structure. After polarization by an external magnetic field H_0 [A/m], the domains with identical or similar orientation grow by shifting of Bloch zones or change the polarization through the Barkhausen effect. When the external field passes, not every domain returns to to its initial state, which leads to residual polarization I_r [T]. Magnetized areas have their own magnetic field with the intensity of H_r [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 I_r. [8], [12], [13]

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

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

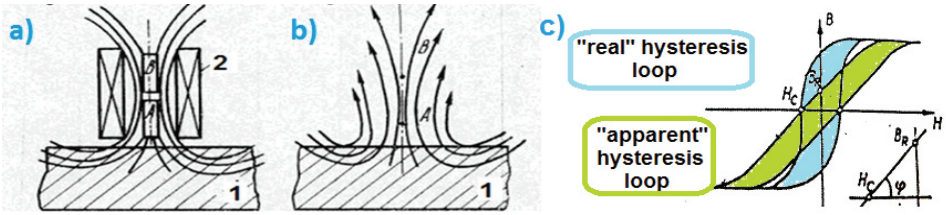

Fig. 1 Magnetic spot - pole method; a) magnetizing; b) measurement; c) linearization of the hysteresis loop in the second quadrant; A, B - Hall sensors; 1 - ferromagnetic material; 2 - magnetizing coil. [8]

Because the controlled parts often have a huge demagnetizing factor N, the relation between the residual induction B_r and the coercivity H_c is linear (see **Fig. 1c**; the linearizing of the hysteresis loop in the second quadrant). H_c often reacts sensitively to mechanical properties, e.g. strength, hardness etc. This principle is used by the magnetic spot-pole method (**Fig. 1 a,b**). A magnetic „spot-pole“ is created on the surface of the tested material by a magnetizing coil inside a probe. While the current pulse in the coil passes, the residual magnetic field H_r on the surface is measured by sensors. These sensors (mostly Hall sensors) are connected differentially to measure the gradient of the tangential or normal parts of the field. [10], [14]

As mentioned above, the value of H_r is related to the structure/matrix of the ferromagnetic material. This provides a measurement of hardness, strength or hardened depth. It was found that by repeatedly magnetizing it is possible to determine structural components (pearlite, sorbite, martensite) and to detect and measure the depth of decarburization. The correlation between the monitored quantity and measured intensity of the residual magnetic field must be experimentally determined and the device then must be calibrated. The method has successfully been applied to steel and cast iron, however, its most common use is for interoperating control of castings (through *HB* or R_m). The 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 take into account the marginal effect, the effect of the thin walls and the shielding effect (diamagnetic graphite) in order to improve the results. The influence of temperature can also be significant as Hall sensors are made of semiconductor

materials. It is necessary to measure the shot-blasted surface without residual ferromagnetic oxides, which have a huge influence on H_r. [8], [12], [15]

Both the magnetic and ultrasonic methods are already known in the field of NDT inspection of steel products and iron castings - see e.g. [8] to [14]. The dependencies between the structural parameters and the properties of these materials have been researched and successfully applied. Non-monotonic dependencies are expected in the case of austempered iron with an unusual structure - with a high content of paramagnetic austenite and considerable influence of graphite morphology and therefore they must firts be carefully observed and assessed. That is the reason why two kinds of structuroscopy are used, because the have a different sensitivity to the structural influences.

2.2. Experiments - short review

A set of reference samples of cast iron of lamellar, spheroidal and vermicular graphite was created for the experiments (for the chemical composition see **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 of 240, 310 and 400°C for 2, 10, 30 and 60 minutes, and final cooling in air. This provided the structure of the lower, upper and transition (middle) ausferrite.

Table 1 Chemical composition of the 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

The experiments were carried out according to the following schedule:

- measurements on a wide set of ADI/AGI samples with a matrix of lower and upper ausferite using of conventional methods to obtain the necessary data of physical and mechanical properties of the material
- measurements using NDT structuroscopy to obtain the necessary parameters of the structure
- interpretation of results, data analysis
- dependencies between the structural parameters and the physical quantities to specify how the NDT methods will be applied for the measurement of on a wide set of austempered castings
- calibration of instruments and testing of procedures under real production conditions

2.3. Major dependencies between austempered structure and acoustic properties

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

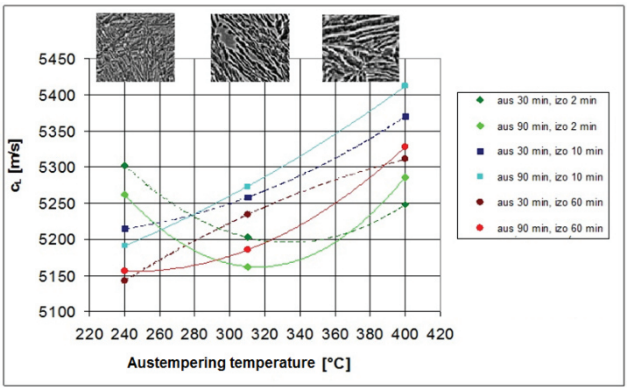

Fig. 2 The dependence of c_L on HT conditions (AVGI)

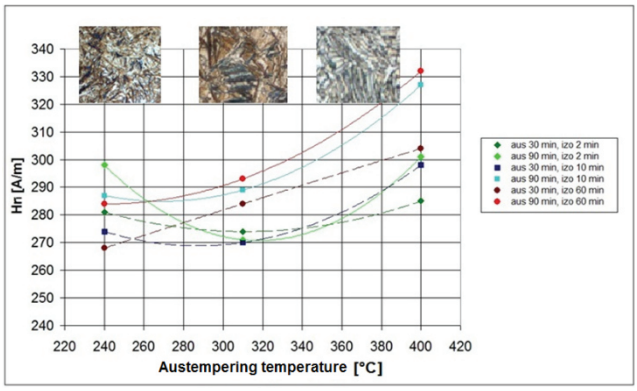

Fig. 3 The dependence of H_r on HT conditions (AVGI)

2.4. Major dependencies between the austempered structure and magnetic properties

The results of the magnetic measurements show that while the iron in an as-cast state influences the value of the residual magnetization mostly by its mechanical properties (i.e. H_r increases linearly with hardness and strength), after the austempering process the main influence on H_r is given by the content of paramagnetic stabilized austenite. This influence is dominant and covers all of the other influences, such as graphite, mechanical properties, etc. The value of residual magnetization is several times higher compared to the as-cast state. This is caused by the specific structure, which is similar to the composite of ferromagnetic ferrite needles/laths with a binder of paramagnetic austenite. Hence, the structure represents thin layers of ferromagnetic material, which are separated by non-ferromagnetic insulation, so the influence of the wall thickness is summarized along with the shielding effect - the same effect has been observed in the 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 as the "magnetic hardness" of the material increases. The value of the residual magnetization increases with increasing content of stabilized austenite. This dependence is nonlinear (see **Fig. 3**).

The total value of the residual magnetization H_r as well as the difference between the first and second magnetization from the virgin state - dH_r can be reliably use to check the effect of the HT. As shown in **Table 2**, the different ranges of values corresponding to individual structures are relatively smoothly linked.

Table 2 Table of dH_r values depending on the 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 H_r/dH_r can be reliably combined eg. with austenite content or can be successfully used for the detection and measurement of undesirable decarburization. The use of values of residual magnetization is not very reliable for the determination of the mechanical properties (esp. strength) as in the case of as-cast iron due to the opposite effects. To determine the mechanical properties it would be necessary to establish multiparametric dependencies based on both magnetic and ultrasonic parameters with a much larger data file.

3. CONCLUSIONS

An inspection procedure was based on the above-mentioned dependencies - see **Fig. 4**.

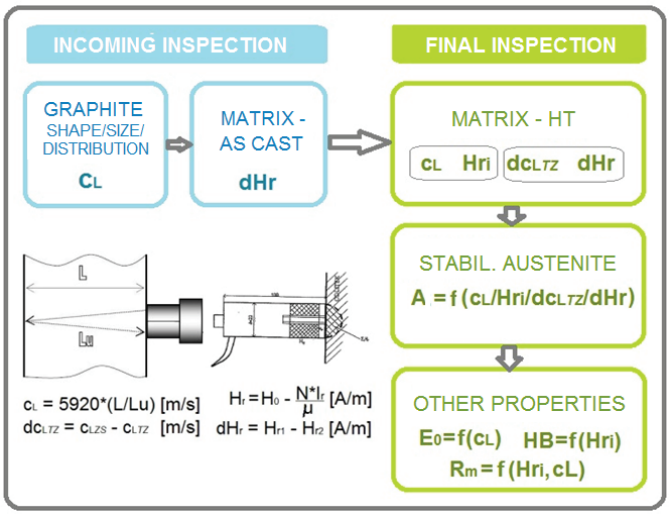

Fig. 4 Diagram of the inspection using ultrasonic speed and residual magnetization.

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

It should be noted that the dependencies were determined using laboratory samples under optimal conditions (esp. excluding the influence of shape or wall thickness). Verification of the dependencies is currently being performed together with the implementation of inspection procedures in the production of specific parts made of austempered irons (ADI and AGI). Since these are generally thin-walled castings with a circular shape, it is necessary to correct the dependencies due to the influence of wall thickness and the radius of curvature. In further work it will be necessary to extend the existing values with more austempering temperatures and dwells.

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

ACKNOWLEDGEMENTS

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