QUANTITATIVE NDT STRUCTUROSCOPY OF CAST IRON CASTINGS FOR VEHICLES (CARS AND LOCOMOTIVES)

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Abstract: Cast irons as a "composite" from steel matrix and graphite filler. The semiproducts of automotive and railroad vehicles safety parts are still cast iron castings. The standard description of matrix and graphite structure properties e.g. after EN 945 is not satisfactory. Physical description - of graphite structure by rigidity - of matrix by hardness. The expression of this description in a plane using bidimensional vector of tension strength or yield strength offers new useful relations to manufacturing metallurgy. The MAT method is developed for thin-wall castings. Magnetic adaptive testing (MAT) is shortly said magnetic hysteresis NDT method exploiting large datafile created by voltage impuls induced in detection coil winded onto specimen, in dependence on immediate value of magnetic field of specimen. The specimen is hereat gradually magnetised by sequence of minority magnetisation loops of variable magnetisation field from minimum possible upto saturation amlitude. MAT results are typically more sensitive and measurement is experimentally more friendly than conservative hysteresis tests. The combined testing by device for remanent magnetism measurement and ultrasound impulse device with its touching probes placed onto surface of as-measured object (casting) together with wall-thickness tester for thick-wall castings (from 20 mm). They are connected together with couppling vector unit with numerical or graphical representation of vector on display, which cosists from both magnetic (characterizes metallic matrix) and acoustic component (characterizes graphite).

Key words: magnetic method, structuroscopy, cast iron, clutch disks

1. INTRODUCTION

Cast irons creat "composite" from steel matrix, in which are placed variously oriented graphite formations with maximum size several tenths of mm. Excellent thermal conductivity of graphite causes high I values. Graphite transfers only compression loading. It has no tensile strength.It decreases cast iron rigidity considerably (it means elasticity modulus value E as well) in comparison with steels. Cast irons don´t shrink due to "graphite growth". It enables to cast substaially homogeneous castings of castings for vehicles, for example engine cylinder, brake and coupling disks disimilarly from Al and Cu alloys. High sher stregth values ts=0,9Rm of disks can be achieved by stable strong matrix - usually pearlite. Ferrite formation is not allowed. Shape of graphite and final matrix structure is determined by casting metallurgy. Casting metallurgy process reproducibility is influenced by raw material composition, process temperatures and duration senzitively. Effective checking activity is necessary to ensure quality of cast iron casting with narrow tolerances of mechanical properties and homogeneity. Its effectivity is based on checking just onto casting without its destruction and speed (it doesn´t brake manufacturing flow), that enables operative correction of eventual properties deflections from technical specifications.

1.1. CAST IRONS

Basic classification of graphitic cast irons is given by shape of graphite after ISO 945.

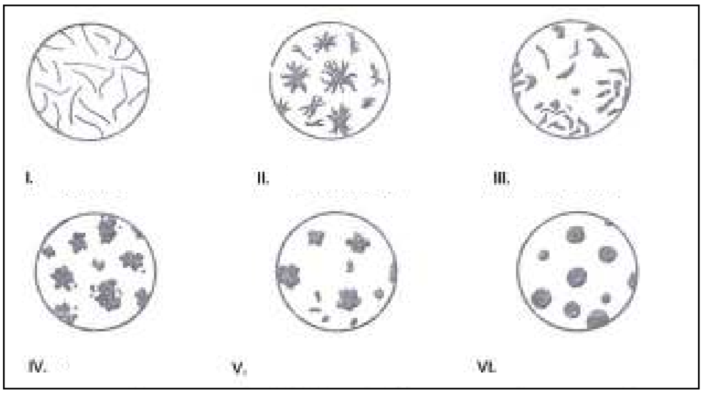

Fig.1: Standardized shapes of cast iron graphite: I - flake, II - crab-form, III - vermicular, IV - temper, V - globular and VI – spheroidal.

Cast iron with flake graphite is commonly used of quality GJL-250 or czech equivalent ČSN 42 2425. It achieves values of properties after Table 1 at plates (thickness from 15 to 30 mm) of brake and clutch wheels cast at SKS Krnov. Cast iron is melted in cupola furnaces. The aim of program project BONATRANS is obvious from its name „Research of manufacturing technology of castings from cast iron with spheroidal graphite by modification in casting mould". Cast iron with spheroidal graphite is made from cast iron with flake graphite by Mg modification. Magnesium enhances surface tension of liquid cast iron considerably. It forces graphite growth in spheroidal formation, not in flakes. Sulfur content of cast iron is necessary to lower below 0,02 % before modification. If it is not done modification doesn´t occur. Sulfur content is lowered using active slag (O2 blowing) and into liquid cast iron continuously introduced filled (desufurizing agent) profile. Applied INMOLD modification (reaction chamber in mould).

EN	ČSN	Rm (Mpa)	A5 (%)	Rd (MPa)	& (μm/mK)	λ (W/K.m)	Eo (Gpa)	EF
GJL-250	42 2425	>250	0,3-0,8	600	11.7	46.5	125	7.95
GJS-600	42 2306	>600	>3	870	12.5	31.1	174	8.58

Tab.1: Properties comparison of mentioned cast irons

Resistance against thermal shock can be specified by Eichelberg factor EF.

$$EF = Rm \cdot \lambda/(\alpha \cdot E) \qquad (1)$$

Mentioned properties values react senzitively to changes of metallurgy process of disks manufacturing. Cumulation of less favorable (but still tolerant) temperature changes, time regime or chemical composition can led to unallowable deflections of usefull properties of casting. For this reason the part of project was development and implementation of checking non-desstructive structuroscopy methods to cover planned 100% disk production.

2. NON-DESTRUCTIVE MEASUREMENT OF CAST IRON MECHANICAL PROPERTIES

The branch of NDT has its own organization structure in single countries. The rigid qualification order (EN 473) of workers competent to testing, unambiguous terminology, requirements for certification of measurement technique and competency of sites and labs in single testing methods is stated by 182 national standards [1].

Most of them has general character or deals with steel weldments, pipes, pressure vessels, bars and forgings. 18 standards contain casting testing by non-destructive procedures in their names, about 10%. Branch activity of NDT with all standards is dealing with classical defectoscopy, i.e. with techniques of searching and presentations of continuity deffects. The RT and UT methods for internal defects a and MT and PT for surface ones are resolutely validated and become the subject of acceptance terms in foundry.

Non-destructive structuroscopy remain apart from mentioned view of standards, without unifying element. It is a subject of development. But in specific cases, esspecially in cast iron foundry its importance for quality final casting manufacturing prevails over defectoscopy. The structuroscopy quatifies the relation between physical non-destructively measured measured quantity and mechanical property, metallography parameter or (mechanical) tension.

2.1 ULTRASOUND METHODS

Acoustic waves permeability through material decreases with damping of matrix mass and esspecially with amount and size of internal discontinuities. As a discontinuity can be considered inclusion with substantially different resistance Z against matrix [2].

$$Z = c \cdot \rho \quad [\text{MPa/s}] \qquad (2)$$

The amount of reflected pressure of acoustic wave from boundary back through steel matrix of cast iron increasis with increasing difference between acoustic resistances Zm and Zg.

$$R = (Zg\text{-}Zm)/(Zg\text{+}Zm) \qquad (3)$$

$Zm=5{,}92 \cdot 7{,}2 = 46{,}2$ [MPa/s] is valid for cast iron steel matrix.
$Zg = 2 \cdot 2 = 4$ [MPa/s] is approximately valid for graphite.

Boundary matrixe – graphite reflects R= 80,5% acoustic wave pressure. Direct propagation of acoustic wave through cast iron is after several reflections from graphite formations spent and dissipated. Thus path size of acoustic wave through matrix depends on graphite formations labyrinth. The value of acoustic path Lu in comparison with direct path (as-irradiated wall thickness) L increases with with weakening of matrix by graphite formations. Thus sound velocity sinks.

$cL = cL0 \cdot L/Lu = 5920 \cdot L/Lu$ [m/s] (4)
cL0...sound velocity of cast iron steel matrix.

If metastable crystallization of eutectics in the fasterly cooled part of casting occurs (it means that carbon is binded to iron in the form of carbide Fe_3C and separates out as a hard ledeburite instead of graphite formation), there are less obstacles to acoustic wave propagation through casting and therefore sound velocity value increases with in creasing amount of ledeburite in structure. Acoustic oscillation amplitude damping α increases markedly if the wavelength λ appraoches to size of graphite formations l.

$\alpha = k\alpha \cdot l \cdot (\tilde{c}_L/\lambda)^2$ [dB/mm] (5)

Value α=0,05 for steels enables to sound through one meter wall thickness as well. The graphite increases damping considerably. For cast iron with spheroidal graphite α reaches values of hhigher order, it limits greatly defects detection. The most of castings can characterized by their own resonance frequency fr, which is a function of elasticity modulus E (it describes graphite shape), specific weight (amount of graphite) and slenderness ratio H/D. Frequency fr occurs in audible range usually.

$fr = kf \cdot (E/\rho)^{0,5} \cdot D/H^2$ [Hz] (6)

E value depends on sound velocity size cL directly and hence on shape and amount of graphite.

$cL = \{(E/\rho) \cdot (1 - \mu)/[(1+\mu) \cdot (1 - 2 \cdot \mu)]\}^{0.5}$ [m/s] (7)

The simplified expression can be obtain by editing of (8), where L is actual wall thickness and Lu wall thickness measured by ultrasound.

$E = (K \cdot L/Lu)^2$ [MPa] (8)

2.2 IMPULSION MAGNETIC METHOD

It is focused on local measurement of remanent magnetism Hm with balistic (impulse) mode of magnetization [3]. Atoms with the same magnetic orientation in steels are centralized in domains, which form any subgrains in structural grains. The growh of domains occurs at polarization by exernal magnetic field by shift of Bloch zones and by polarization identical with external magnetic feld or jump change of polarization by so called Barkhausen jumps (source of Barkhausen noise). After disappearance of external magnetic field all domains don´t return to original stage. Remanent magnetization Ir is created. The magnetized site has its own magnetic field with intensity Hr. Ferromagnetics atoms bound in molecules, atomic tensions and lattice imperfections prevents to reversible changes. For this reason structure constituents containing. Iron carbide, martensite, numerous dislocations and grain boundaries show high density of remanent polarization Ir.

$Hr = Ho - N \cdot Ir/\mu$ [A/m] (9)

Demagnetizing factor N characterizes both external nd structural geometry conditions of ferromagnetics boundary. The impulse magnetic field with intenzity Ho acts on as-tested site of product. Shape of current impulse conducted into surface force coil, eventualy precisely defined their sequence defines flow of parasite eddy currents (they can be used to compensation of negative effects of N properly) and structure selective senzitivity of method. Methods used in Russian and in the Cze Republic differs just essentially magnetization charcateristics and by it in the intention of application. Hr sensor can be Hall or Főrster probe. The contribution dHri of single ferromagnetics grains to final value Hr depends on shielding effect m and on their distance from reader.

$$Hr = \sum(m \cdot ti \cdot dHri) \qquad (10)$$

The effect of single grains on Hr decreases with depth of penetration S of magnetic field. In practice upto t=12mm. Hence the pulse energy in thinner walls concentrares to lesser volume of grains. Hr value increases upto value Lkri after experimentally determined model.

$$Hr_L = Hr_{L12} \cdot (81 \cdot L\text{-}3+1) \qquad (11)$$

Iron alloys (steels and cast irons) create the spectrum of most widespread structural materials. The ferromagnetic properties can be assigned to their general most. Knowledge of mechanical property values at critically loaded site of exposed parts dominate over need of integral information about choiced mechanical property. For this reason the local magnetic structuroscopy ownes an important position in the spectrum of other methods. It found its application expansion in the form of impulsion magnetic checking mainly in Russian and Bohemia.

It can be characterized by high productivity of checking with goal-directed senzitivity to as-checked structure parameter. In the west Europe is used for this region of materials ET method exclusively. But alternative eddy currents describes surface sections of parts more. For products in the form of worked semiproducts and castings with untreated surface the local magnetic structuroscopy matches better.

2.3. Magnetic adaptive testing

Magnetic adaptive testing (MAT) is shortly said magnetic hysteresis NDT method exploiting large datafile created by voltage impuls induced in detection coil winded onto specimen, in dependence on immediate value of magnetic field of specimen. The specimen is hereat gradually magnetised by sequence of minority magnetisation loops of variable magnetisation field from minimum possible upto saturation amlitude.

MAT purpose is to find descriptors of used specimens observed changes in this datafile which are optimal just against observed changes of used material. The functional dependence eventualy dependences of such descriptors on observed material changes are marked as degradation functions. MAT results are typically more sensitive and measurement is experimentally more friendly than conservative hysteresis tests [5].

The cast iron is hererogeneous alloy of iron and carbon containing large amount (more than 2 %) of carbon undissolved in iron (in opposite to steels). It is typically a mixture of ferrite and pearlite plus inclusions of diamagnetic graphite. The cast iron is ferromagnetic material and for this reason there is no surprise that it is suitable candiadate for testing with magnetic methods, e.g. MAT.

2.3.1. Testing of ferrite/pearlite ratio

Because to main constituents of cast iron, ferrite and pearlite generally own fundamentally different magnetic properties (ferrite is rather magnetic soft, pearlite is rather magnetic hard), it can be expected that MAT is able to distinguish one from another cast irons with various ferrite/pearlite ratio. It can be proved e.g. by diagram given in Fig.1. and it can be supposed that such magnetic measurement shall be applicable for NDT of ferrite/pearlite ratio of cast irons after detailed experimental verification. The dependence of suitable magnetic descriptors on cast iron ferrite/pearlite ratio is evidently demonstrative and powerful, descriptor value is able to change in multiples.

2.3.2. Testing of graphite inclusions shape

There is occasion to use sensitive MAT measurement for another industrialy important tests as well, namely to determination of cast iron graphite inclusion shape, if dispose with cast iron specimens with constant ferrite/pearlite value. The graphite inclusions shape viz. is decing factor that determines cast iron material quality. Inclusion shapes can be characterized by scale of designation GI, GII,... upto GVI, to which corresponds illustration of inclusion shape fro GI (foliated), ...through GIII (vermicular),... to GV (globular) and finally GVI (spheroidal), Fig.2. Thus GI corresponds to brittle grey cast iron , upto GVI corresponds to ductile cast iron with properties corresponding in practice to quality steel. Fig.3 shows that MAT is able to distinguish fine differences, because its degradation functions corellate very well with sound velocity in single specimens (the shape of cast iron inclusions in the cast iron and in that way cast iron material quality can be rated by ulrasound velocity measurement). The dependence of suitable magnetic descriptors on cast iron graphite inclusions shape is evidently probatory as well, but it is weaker than dependence on ferrite/pearlite ratio, descriptors value is able to vary in order of tens of percents.

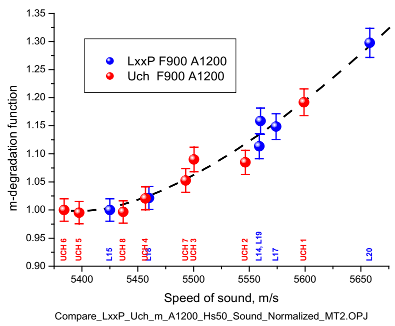

Fig.3 Degradation function dependence of differential permeability (for MAT – field coordinates F=900 A/m, A=1200 A/m) on sound velocity of cast iron samples. Degradation function is regulated to sample with sound velocity about 5400 m/s (low GVI + GV content – upto 50%).

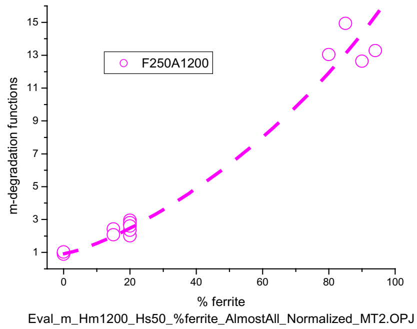

Fig.2 Dependence of differential permeability degradation function (for MAT – field coordinates F=250 A/m, A1=1200 A/m) on ferrite content of cast iron samples. Degradation function is regulated to sample with 100% of pearlite (0% of ferrite).

3. STRUCTUROSCOPY OF BONATRANS DISKS

Chapter exploits knowledge of internal report [4].

The aim of checking operations is to ensure the delivery of castings with mechanical properties within given tolerances. Boundary values of HB, Rm, Rp, A important for releasing of castings to delivery prescribe technical delivery conditions (TDC) TP22–112–04. In the years 2005 and 2006 in the frame of campaign of development melts were cast tens of testing disks of Y2 blocks and flat samples with large-scale structure. After non-destructive measurement were determined mechanical properties and metalography destructively. By regression analysis of both non-destructively and destructively measured data were determined mathematic models to memories of DOMENA and TELIT aparatuses.

Fig.4: DOMENA B3

Fig.7: TELIT with readers on testing plate.

3.1 MAGNETIC STRUCTUROSCOPY – DOMENA B3

The aim of research was to determine linear equations (constants A, B) for calculation of mechanical properties inserted into memory of DOMENA B3 (Figure 2) before measurement. Optimum regime was set to magnetization M4 or M5. During the solution of project was made an effort for improvement of measurement reproducibility after reproduced measurement and measurement at low and high temperatures. (+-300C). On basis stability measurement results the manufacturer of DOMENA B3 (ELKOSO s.r.o. Brno) implemented technical changes to performance stability improvement. Generally:

$$HB=A \cdot M+B \tag{12}$$

Hardness measurement on castings and disks from cast iron with spheroidal graphite.

$$HB = 0,6 \cdot M + 100 \tag{13}$$

Measurement of mechanical properties on disks from cast iron with spheroidal graphite.

Property	Equation	Δ	K K2
HB	0,8·M+128	10	0,958 0,918
F [%]	116 – 0,585·M	10	-0,932 0,868
Rm [Mpa]	2,69·M+383	26	0,955 0,912
Rp0,2	1,81·M+242	32	0,931 0,867
A [%]	22,4-0,09·M	2	-0,89 0,787

Tab.2: Measurement of mechanical properties on disks from cast iron with Δ…medium verified measurement error

Measurement of Rm, Rp, A je is qualified with satisfactory high value of elasticity modulus over 160 GPa, which ensures high share of spheroidal graphite in the structure. It is necessary to prove it by universal defectoscope USN35. This checking procedure is replacing measurement instead of TELIT.

3.2 RIGIDITY Eo OF CAST IRONS

The formulas serves both for general work with USN35 and iinsertion into memory of TELIT before measurement. After Eo value can be unambiguously determined quality rank of cast iron with spheroidal graphite for given wall-thickness. For cast iron with flake graphite SKS used still for BONATRANS disks is valid:

Eo = (446,1 · L/Lu)2 (14)

Boundary values contains Table 3 in the report [4]. For disks is valid:

ČSN quality	Eo [Gpa]	VL [m/s]	L/Lu
Lower limit	97	4133	0,6982
42 2420	102,2	4242	0,7166
Boundary 20/25	111,1	4423	0,7472
42 2425	120	4597	0,7765
Boundary 25/30	126	4711	0,7957
42 2430	132	4821	0,8144

Tab.3: Boundary values E0 of cast iron according to ČSN

Values L/Lu serves for operative rapid checking.

Cast iron with spheroidal graphite:

Eo = (432,57 · L/Lu)2 (15)

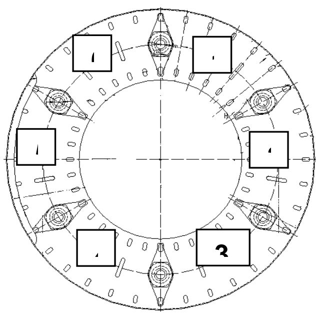

Fig.5: Measurement sites on plate (L=30mm) of disk B1493

Average rigidity of disks BONATRANS (Figure 3) Eo = 171,7GPa. In foundry oractice of ladle modification procedures is satisfactory to measure L/Lu of first and last casting cast from charge of modified cast iron of ladle usually. In SKS developed INMOLD modification requires to to prove modification efficiency of each casting from mold.

Boundary values of sound velocity vL resp. only rate L/Lu with regard to boundary values after EN for rapid estimation of cast iron with spheroidal graphite satisfactory nodularity is valid Table 4.

Quality after ČSN	Eo [Gpa]	VL [m/s]	L/Lu
42 2304,5	160	5475	0,9247
42 2306,7	170	5642	0,9532

Tab.4: Boundary values E0 of cast iron with spheroidal graphite according to ČSN

EN standards are ambiguous at allocating Eo values. Value of 160 GPa corresponds to 25-35% share of vermicular GIII at the expense of spheroidal GVI graphite in cast iron structure. Strict technical delivery conditions TP 22-112-04 requires to keep boundary value 170 GPa.

3.3 CHECKING BY UTILITY DESIGN TELIT

Equipment for non-destructive determination of material quality under type label TELIT, that is result of development in the frame of project F1-1M/01, after utility design CZ17380 (Figure 4) measures input quantities M, L, Lu. By mathematical models

$$HB = A \cdot M + B \quad (16)$$
$$Eo = (K \cdot L/Lu)2 \quad (17)$$
$$Y = C \cdot (L/Lu)D \cdot ME \quad (18)$$

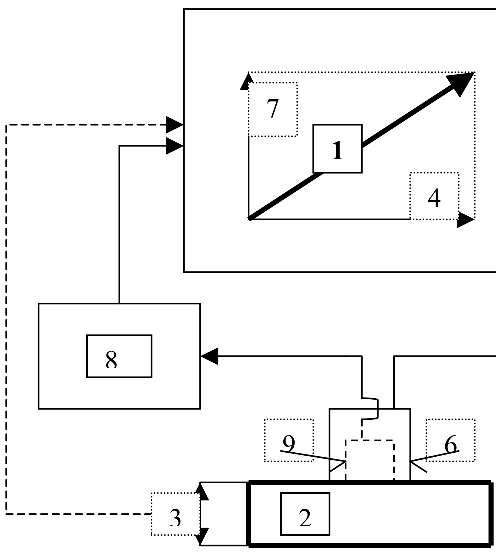

Fig.6: TELIT: 1. vector of structure, 2. disk, 3. disk thickness, 4. cast iron rigidity, 5. impulsion magnetic hardnesstester, 6. magnetic reader, 7. constituent (hardness) of cast iron matrix, 8. ultrasound thicknessmeter, 9. ultrasound probe, 10. composing unit (PDA).

Then HB, Eo, Y where Y is Rm strngth, Rp yield strength and A ductility.

For cast iron with spheroidal graphite castings is valid :

HB=0,6 · M+100 (19)
Eo=(446,1 · L/Lu)2 (20)
Rm=7,211 · (L/Lu)2,278 · HB0,75 (21)

For disks from cast iron with spheroidal graphite:

Rm = 8,54 · (L/Lu)5,257 · HB0,86 (22)
Rp = 9,3 · (L/Lu)3 · HB0,756 (23)
A = 132000 · (L/Lu)13 · HB-1,635 (24)

Verified mean error Rm, Rp, A upto 10%.

4. CONCLUSIONS

Average checking cadence with magnetic hardnestester DOMENA B3 is 3-5s and with combined structuroscope TELIT 5-20s (after parallel or seria regime of reader measurement). As-calculated mathematic models enable to measure mechanic properties with satisfactory accuracy. The solution of region of NDT of structure by project F-1M/01 shall ensure 100% production checking of both as-developed (from cast iron with spheroidal graphite) and existing BONATRANS disks. Series of particular knowledge exceeded specification range. Their appropriation and introduction to industrial practice of other foundry shops by project owner is of great importance. Presentation of results in structure plane HB-E and diagnostics of inherent defects is part of future development apparatus TELIT.

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