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Influence of Structural Parameters - the Shape of Graphite and Matrix on Change of Ultrasonic Wave Propagation Rate and Value of Attenuation in Graphitic Cast Irons

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Abstract
Despite the tendency of the current industry, especially the automotive industry, it is to use modern, light and super-strong materials based on Al or HSLA steels, the application of classic materials such as cast iron still makes sense, especially concerning price and excellent castability. The article presents one of the possible ways of using the ultrasonic non-destructive method in quality control and simplification of the identification of the type of cast iron concerning the change of parameters of ultrasound propagation in materials. The main criteria for assessing the quality and determining the type of graphite cast iron were considered to be the rate of propagation of ultrasound - c_L and the value of attenuation - α, which vary depending on the shape of the graphite and matrix. Graphitic cast irons with different graphite shapes (lamellar, vermicular, and globular shapes) and a matrix with different ferrite/perlite ratios were used as experimental material. Along with the ultrasonic tests, a metallographic analysis was also performed to quantify the microstructure of cast irons.

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1. Introduction

Graphite cast irons have found application in several industries in recent decades. They have found application in the automotive industry in the production of crankshafts, pistons and cylinder heads, friction bearings and gearboxes. Based on the shape of the excluded graphite, we can divide graphite cast iron into three basic groups. The natural form of graphite, which occurs during casting and without additional melt treatment, is the so-called lamellar graphite. After treatment of the melt with modifiers such as Mg, Ce, Ti or rare earth metals, the original shape changes from flake to vermicular (transition shape between lamellar and perfectly grained graphite). The graphite-shaped vermicular cast iron is the result of finding a suitable ratio of elements such as Mg + rare earth metals (RE) and which have a strong globulization effect and Ti, which has an antiglobulizing effect. The last basic type of graphite is perfectly grained graphite. Of course, in addition to the already mentioned basic shapes of graphite, there are also flake shapes, which are the result of heat treatment of cementite - tempering and graphite so-called "arachnid". However, cast irons with the latter graphite shapes have not found such a wide technical application as cast irons with the basic type of graphite. Due to its mechanical properties, cast iron with a perfectly grained graphite shape has higher strength and ductility than cast iron with a lamellar graphite shape of similar chemical composition (Ulewicz et a. 2014). Gray iron inoculation is widely practised and involves adding Si or Al to the liquid metal shortly before solidification. When the residual magnesium content in the melt is sufficient, the graphite grows into a spherical shape. Otherwise, various degenerate forms of graphite may be formed, such as flake graphite; in this case, the sharp edges of the flakes cause critical stress concentrations, which have a more adverse effect on the mechanical properties than compacted graphite forms with rounded ends. Regardless of whether the matrix is fully ferritic or pearlitic or other combinations, changes in graphite size and shape can be caused by changes in chemical composition, casting cross-sectional thickness, design, and casting conditions.

One of the possible methods of quantification of structural parameters such as graphite shape and ferrite/pearlite ratio in the graphite cast iron matrix is the use of non-destructive control methods, namely the ultrasonic method. The basic principle of ultrasonic quality control is the use of elastic and anaelastic interaction between the sound wave and the microstructure. Indirect evaluation of graphite morphology is possible by ultrasonic velocity measurements, which are also dependent on mechanical properties. Another alternative is to evaluate the ultrasound attenuation. The microstructure of graphitic cast irons is formed by differently sized and differently oriented ferrite grains resp. perlite or a mixture thereof and the precipitated graphite particles in various forms, as mentioned above. These structural components have significantly different elastic properties. Although the material as a whole exhibits isotropic properties due to the random grain orientation, the elastic anisotropy and the different orientations of the crystallographic axes concerning the axes of the adjacent grains cause the modulus of elasticity to vary from grain to grain. The grains may also vary in density due to the different phases present. Thus, sound waves will be affected by sudden changes in propagation speed and corresponding changes in their characteristic impedances, and reflections will occur at grain boundaries or interfaces.

Throughout the past decades' several studies related to this topic had been published. The use of ultrasonic non-destructive evaluation in the identification of graphite shape in castings with perfectly grained graphite and ferritic matrix has been published by (Emerson et al., 1976) Authors (Collins et al., 1995) have discussed the matrix structure and graphite shape on ultrasonic wave propagation and attenuation volume. They found that for graphite nodularity of 80%, the longitudinal wave propagation speed was about 5600 m.s^{-1}, and this velocity dropped to about 5200 m.s^{-1} at nodularity of about 30%. Below this value, the ultrasound speed decreases faster to approximately 4200 m.s^{-1}, which corresponds to a cast iron with a lamellar type of graphite. At the same time, they noted that at the probe frequency (instrument excitation) of 4 MHz and 2 MHz, the influence of the matrix structure on the ultrasound attenuation was highest at the martensitic structure and gradually decreases as the structure changed from pearlitic to ferritic. Authors (Fuller, 1977; Fuller et al., 1980) have published a similar study, but for pearlitic cast iron. Later on, authors (Lee et al., 1989; Lerner et al., 1996; and Orlowicz et al., 1995) published works about using ultrasonic non-destructive testing at microstructure and graphite nodularity prediction or castability prediction.

The determination of the vermicular graphite ratio to ultrasonic methods parameters was published by authors (Liu et al., 2018) and (Tupaj et al., 2020). From their work results, the change in ultrasonic velocity is depending on the angle of graphite particles. With increasing graphite angle from 0° to 0.5°, (graphite becomes more rounded) the ultrasonic velocity increases about 25 m.s^{-1}. On the other hand, the influence of the ferrite/pearlite ratio on ultrasonic wave speed has changed slightly, about 22 m.s^{-1} at an increased ratio from 24% to 87%.

Similar results about ultrasonic velocity and attenuation were obtained for nodular cast iron. El-Hadad et al. (El-Hadad et al., 2019) described the influence of Ti content on the ultrasonic velocity and attenuation. They concluded that increased volume of Ti alloying in ductile cast iron distorted the graphite nodules and with decreasing nodularity also decrease the ultrasonic wave speed. Santos et al. (Santos et al., 2021) discussed ultrasonic scattering attenuation in nodular cast iron by using of Truell and Papadakis model for scattering attenuation. A wide study about ultrasonic attenuation of engineering materials was published by Ono (Ono, 2020). He describes the contact ultrasonic measurements methods that can be used for attenuation evaluation in various solid engineering materials such as metals, ceramics, polymers composites, etc. Based on his study, it is possible to divide the behaviour of cast iron into two main types. In the case of ductile iron samples with high strength and toughness with a ferritic matrix, the attenuation of ultrasound was controlled by the so-called Mason-McSkimin relationship, which was caused by the scattering of nodular graphite particles. Samples with the lamellar type of graphite, so-called grey cast iron, showed high attenuation with quadratic frequency dependence.

The paper aims to point out the suitability and complexity of ultrasonic non-destructive testing in assessing the quality and basic structural parameters of cast iron castings with different graphite shapes. These methods are simple to apply and do not require metallographic sample preparation procedures, which leads to significant time savings in verifying the quality of castings.

2. Experimental

Three cast irons with different graphite shapes (lamellar – GJL, vermicular – GJV, and nodular – GJS) and various chemical compositions were used as experimental materials. The chemical composition and eutectic degree of cast irons are in Table 1. The eutectic degree of cast irons is calculated according to Equation 1.

$$\boldsymbol{S_C} = \frac{\%\boldsymbol{C}}{\mathbf{4.3-0.312\%}\boldsymbol{Si}\mathbf{-0.275\%}\boldsymbol{P}} \qquad (1)$$

Where S_C is calculated eutectic degree, %C is the weight percentage of carbon, %Si is the weight percentage of silicon, and %P is the weight percentage of phosphorus.

With the eutectic degree, increasing is ultrasonic longitudinal wave speed decreases, Fig. 1. On an opposite site to strength when with increasing strength is also increasing ultrasonic longitudinal wave speed, Fig. 2.

Table 1. Chemical composition of cast irons with eutectic degree S_C

	Chemical composition in wt. %							S_C
	C	**Si**	**Mn**	**P**	**S**	**Cr**	**Cu**	
GJL	2.98	3.14	0.50	0.022	0.015	0.28	0.06	0.89914
GJV	3.31	2.95	0.52	0.03	0.048	0.04	0.04	0.9818
GJS	3.63	3.99	0.40	0.05	0.027	0.10	0.01	1.19354

Metallographic specimens were prepared regularly and evaluated with quantitative metallography methods – by metallographic software NIS Elements. Microstructures were evaluated according to standard STN 42 0461.

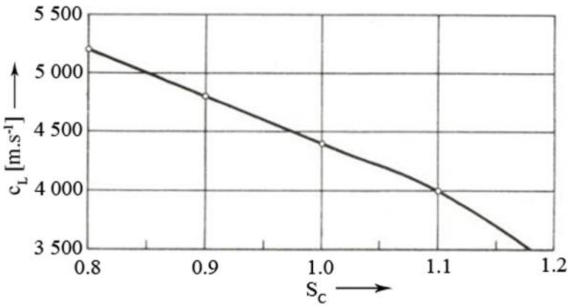

Fig. 1. Dependence of ultrasonic rate cL in GJL according to eutectic degree S_C.

Ultrasonic measurements and results obtained using STARMAN DiO 562 – 2CH ultrasonic flaw detector and materials characteristics were calculated using of following Equations, (Skrbek, 2006):

$$c_L = c_{LO} \times \left(\frac{L}{L_U}\right) \quad [\mathrm{m.s^{-1}}] \quad (2)$$

$$E = \rho \times c_L^2 \times \left\{\frac{(1+\mu)\times(1+2\mu)}{(1-\mu)}\right\} \quad [\mathrm{MPa}] \quad (3)$$

$$G = \frac{E}{2\times(1+\mu)} \quad [\mathrm{MPa}] \quad (4)$$

$$K = \frac{E}{3\times(1-2\mu)} \quad [\mathrm{MPa}] \quad (5)$$

$$\alpha = k_\alpha \times l \times \left(\frac{c_L}{\lambda}\right)^2 \quad [\mathrm{dB.mm^{-1}}] \quad (6)$$

Where symbols used in equations are as follows: c_L is ultrasonic longitudinal wave speed; c_{LO} is ultrasonic wave speed in steel standard = 5920 $m.s^{-1}$; L is the thickness of wall measured by the ruler; L_U is the thickness of wall measured by ultrasonic flaw detector; ρ is density $kg.m^{-3}$; E is the Young modulus of elasticity; G is the shearing modulus; K is the volume modulus; μ is Poisson's constant; α is the attenuation of acoustic vibration amplitude; l is the size of graphite particles (mm), and λ is the wavelength (mm).

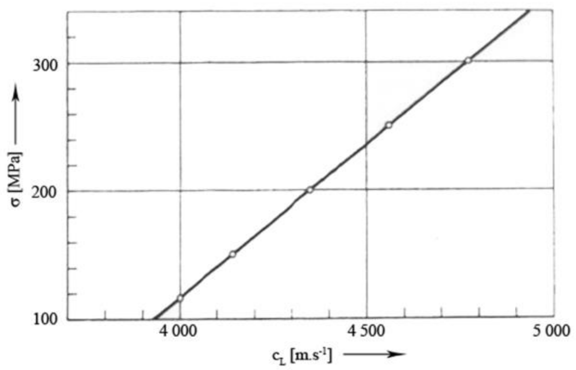

Fig. 2. Dependence of tensile strength σ of GJL according to ultrasonic rate c_L.

3. Results and discussion

From the eutectic degree calculation results (see Table 1) is GJL (cast iron with the lamellar graphite shape) considered hypoeutectic cast iron ($S_C < 1$) as well as GJV (cast iron with the vermicular graphite shape). The last cast iron specimen, GJS (cast iron with the spherical graphite shape) is considered hypereutectic ($S_C > 1$). The eutectic degree is related to castability properties, when closer or equal to $S_C = 1$ the better castability. The quantitative evaluation of cast irons microstructures according to standard STN 42 0461, Fig. 3a – 3c shows that specimen N° 1 is cast iron with lamellar graphite shape (I) where 70% of flakes are with size 120 ÷ 250 μm have mixed distribution in the matrix (C), rest of flakes are interdendritic distributed, where 10% have size about 15 ÷ 30 μm and 20% size about up to 15 μm: 70%IC4 + 10%ID7 + 20%ID8. Specimen N° 2 is cast iron with 80% of vermicular graphite shape (III G) and 20% of undershapen nodular graphite (V) with a size of about 60 ÷ 120 μm: 80%IIIG + 20%V5. Specimen N° 3 is cast iron with 40 % of nodular graphite (VI) of the size of about 30 ÷ 60 μm and 60% of undershapen nodular graphite with a size of about 15 ÷ 30 μm: 40%VI6 + 60%V7.

For evaluation of ferrite and pearlite ratio in the matrix was software NIS Elements used. Results are in Table 2. and micrographs related to obtained results can be seen in Fig. 3d – 3f.

Table 2. Area of ferrite in experimental cast irons

Ferrite content (%)		
GJL	**GJV**	**GJS**
5.45	55.68	73.53

After calculation and putting all necessary values into Equations 2 – 6 were received results for ultrasonic testing of cast irons. All results were compared with given values in material standards and show a pretty good correlation, as can be seen in Table 3 and Table 4.

The ultrasonic wave speed in materials is affected by various factors at the same time. The main factors are thickness and hardness of the material, ferrite content as well as shape, size and volume of graphite in the matrix. In cast irons with pearlitic or pearlitic – ferritic matrix is ultrasonic speed significantly lower, about 1200 $m.s^{-1}$, like in irons with ferritic – pearlitic matrix (see Tables 2. and 3.).

Ultrasonic wave speed is also slower at cast irons with lamellar graphite shape in opposite to cast irons with a higher degree of nodularity. Even higher speed of ultrasonic waves has a cast iron with vermicular graphite shape, the difference just 5 $m.s^{-1}$, in comparison to nodular cast iron (see Table 4).

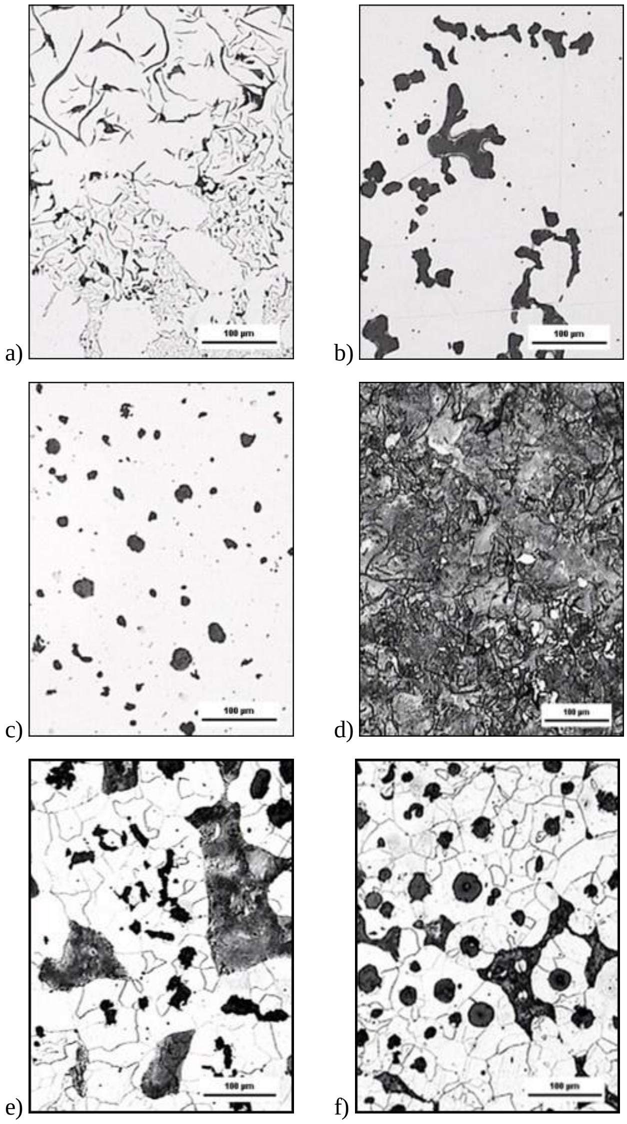

Fig. 3. Microstructures of cast irons for the graphite shape evaluation according to standard STN 42 0461: a) GJL, b) GJV, and c) GJS – all in non-etched conditions; and cast irons microstructures for ferrite ratio evaluation: d) GJL, e) GJV, and f) GJS – all etched by 3% Nital.

Table 3. Values are given by the STN material standard for experimental materials

	L (mm)	L_U (mm)	C_{LU} (m.s^{-1})	μ	E*10^5 (MPa)	G*10^5 (MPa)	k_α
GJL	24.9	31.3	4703	0.26	1.00 - 1.45	0.40 - 0.58	
GJV	15.7	15.5	5912	0.26	1.62 - 1.65		1.96
GJS	14.3	14.2	5960	0.306	1.69	0.637 - 0.657	

Table 4. Results of calculations for ultrasonic testing

	C_L (m.s^{-1})	E*10^5 (MPa)	G*10^5 (MPa)	K*10^5 (MPa)	α (dB.mm^{-1})
GJL	4703.8	1.33	0.53	0.38	0.437
GJV	5996.7	2.12	0.84	1.47	1.64
GJS	5961.7	1.83	1.83	1.57	0.633

However, when the ultrasonic wave is propagate through the material an attenuation – α has appear, which is caused by absorbing and scattering of ultrasound at inhomogeneity and polycrystalline surroundings. The attenuation of ultrasonic waves is depending on inhomogeneity size (in our case – graphite particles) and wavelength. In this case have vermicular graphite shape iron highest attenuation because of the biggest graphite particle size, about 23μm longer than lamellar and nodular cast iron. For comparison see the results for attenuation calculation in Table 4.

In addition to metallography evaluation, also Brinell hardness test according to STN EN ISO 6506-1 standard was carried out. Brinell hardness was provided on the Brinell test machine CV-3000LDB with the loading of 250kp, testing indentor diameter of 5 mm and dwell of 10 sec. Results obtained from 10 measurements on each sample are shown in Table 5. Experimentally achieved hardness was confirmed with the calculation:

$$\mathrm{HBW} = \frac{2F}{\{\pi D \times [D - \sqrt{D^2 - d^2}]\}} \quad (7)$$

Where F is loading force (kp), D is the diameter of the testing indentor (mm) and d is an average diameter $(d_1+d_2)/2$ of the mark (mm) in the material.

Table 5. STN EN ISO 6506-1 Brinell hardness measurements

Specimen	GJL	GJV	GJS
The average value of d	1.24	1.25	1.40
Table value of HBW	204	200	159
The calculated value of HBW	193	190	148

The place of hardness measurement has significant meaning because of the cast iron matrix (ferrite, pearlite and graphite, all components have different hardness). Therefore, shape, size and components distribution will affect hardness measurements from this point of view. In general, the higher hardness is obtained in the matrix with higher pearlite volume, because pearlite is a harder compound compared to ferrite. As seen from the results in Tables 2 and 5 where GJL is a pearlitic – ferritic matrix with 94.55% volume of pearlite compared to GJS, which is a ferritic – pearlitic matrix with 26.47% volume of pearlite. The hardness has changed from 193 HBW 250/5/10 to 148 HBW 250/5/10, which is about 30% of the hardness value decreasing.

4. Conclusions

Three different cast irons – lamellar, vermicular and nodular graphite shapes were used as experimental material. Microstructure of specimens was evaluated according to standard STN 42 0641 and with software, NIS Elements were evaluated microstructure after 3% Nital etching. Brinell hardness measurement was also carried out. The ultrasonic wave speed in materials was measured with STARMAN DIO 562 – 2CH and direct probe GEM5 – 10.

The influence of cast iron graphite shape on longitudinal ultrasound wave propagation can be described as follows:

- The speed of propagation of longitudinal ultrasonic waves increases with the change in the shape of the graphite and its rounding. The higher the degree of nodularity, the higher the speed of ultrasound wave propagation in the materials.

The influence of microstructure (pearlite – ferrite ratio) on longitudinal ultrasound wave propagation is as follows:

- The higher pearlite content in the cast iron matrix leads to decreasing in longitudinal ultrasound wave propagation and on the other hand, higher pearlite volume leads to hardness increasing.

The influence of cast iron graphite shape and pearlite – ferrite ratio on ultrasound attenuation is as follows:

- With graphite shape rounding, the attenuation is increasing (the increase is about 44% for GLS and about 300% for GJV) compared to cast iron with the lamellar graphite shape.
- When the ratio of pearlite – ferrite increases (the matrix is more pearlitic), the longitudinal ultrasound wave propagation attenuation decreases.

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结构参数——石墨和基体的形状对石墨铸铁中超声波传播速率和衰减值变化的影响

關鍵詞
超声波调查
铸铁的质量保证
石墨形状
珠光体和铁素体的比例
石墨和基体的定量评价

摘要
尽管当前行业特别是汽车行业的趋势是使用基于Al或HSLA钢的现代轻质超强材料，但铸铁等经典材料的应用仍然有意义，尤其是在价格和性能方面铸造性。本文提出了一种可能的方法，即利用超声无损方法进行质量控制和简化关于材料中超声传播参数变化的铸铁类型识别。评估质量和确定石墨铸铁类型的主要标准被认为是超声传播速率 – cL 和衰减值，这取决于石墨和基体的形状. 具有不同石墨形状（层状、蠕虫状和球状）的石墨铸铁和具有不同铁素体/珍珠岩比例的基体被用作实验材料。除了超声波测试，还进行了金相分析以量化铸铁的微观结构。