ARCHIVES
of
FOUNDRY ENGINEERING

Published quarterly as the organ of the Foundry Commission of the Polish Academy of Sciences

ISSN (1897-3310)
Volume 7
Issue 2/2007
69 – 74

14/2

Potential for evaluation of mechanical properties of cast iron by ultrasonic method

A.W. Orłowicz , M. Mróz
Katedra odlewnictwa i Spawalnictwa, Politechnika Rzeszowska, ul. W. Pola 2, 35-959 Rzeszów, Polska
e-mail: mfmroz@prz.edu.pl

Received on:15.01.2007; Approved for print on: 20.02.2007

Summary

The paper presents several concepts of physical substantiation for the rationale of building the relationships between mechanical properties and the ultrasonic inspection indicators. Special stress is pull on the application of the law of mixtures for this purpose.

Key words: cast iron, ultrasonic method, microstructure, mechanical properties

1. Introduction

In the research on developing of cast-iron quality-inspection techniques there is a noticeable tendency towards evaluating its mechanical properties and structure on the basis of ultrasonic measurements [1-l1]. The usual objection raised to the relationships between tensile strength and ultrasonic wave velocity and attenuation, reported in the literature, is that those relationships arc empirical and have no physical substantiation. Therefore, attempts at developing the issue gain special importance. The purpose of this paper is to provide more insight in the problem.

2. Attempts at providing substantiation for the rationale of building the relationships between tensile strength and the ultrasonic inspection parameter

Concept of utilizing the existence of interatomic forces

Relationship between the immediate tensile strength of a material and the velocity of longitudinal ultrasonic wave propagation may be obtained from initial expression describing the changes in the interaction of atoms versus distance between their centres [12]. The force of interaction between neighbouring atoms is approximately reflected by the formula:

$$F = -\beta \Delta r + \gamma \Delta r^2 \quad (1)$$

where: β, γ are constants for specific type of atoms, Δr - change in distance related to equilibrium distance between atoms in crystal lattice r_o.

If we know the atomic repulsion force, $F = -F_1$, we may write, that $F = \beta \Delta r - \gamma \Delta r^2$. For small changes in interatomic distances it may be assumed that $\Delta r^2 = 0$ and the formula for external force causing strain, Δr, is thus modified to:

$$F = \beta \Delta r \quad (2)$$

A simplified relation reflects a linear relationship between the force, F, and the elongation, Δr, for the elastic range of strains. It is correct as long as the force causes small strains. Dividing the obtained expression by the cross-section area of the crystal lattice, we obtain a relationship between the stress, $\sigma = F / r_o^2$, and strain, $c = \Delta r / r_o$, as $\sigma = (\beta / r_o)\varepsilon$. In this expression $E = \beta / r_o$ is the Young modulus. For brittle materials the yield point corresponds to immediate tensile strength. If we put strain equal to the yield point in the latter relationship and take account of the relation between wave velocity, Young modulus and material density, we obtain an expression as follows:

$$R_{pl} = \frac{\beta}{r_o}\frac{\Delta r_{\max}}{r_o} = 0{,}5\rho^2 c^4 \tag{3}$$

where: ρ - material density, c - the velocity of longitudinal ultrasonic wave.

This expression is very approximate and may only serve to indicate the character of the relationship between tensile strength and the velocity of elastic waves. The actual structure of metals causes a deviation in values of tensile strength and ultrasonic wave propagation velocity compared to theoretical calculations and therefore the above presented relationship is not used in practice.

Concept utilising the Holl-Petch relation

The relationship between the gram size and the attenuation coefficient, as well as that between tensile strength and gram size in steel was mentioned in the paper by D.Aurich and E.Martin [13]. Up to now a number of research efforts [14-17] were performed, with those relationships utilised as a potential starting point.

The attenuation coefficient of ultrasonic wave is equal to the sum of its absorption and scattering coefficients. In metals the losses connected with scattering have a critical effect on the value of attenuation coefficient [18]. The experimental verification of this issue is laid out in papers [18-23].

The majority of experimental studies performed on steel lead to a conclusion that:

- the attenuation of ultrasonic waves may be utilised for the measurement of grain sizes,
- application of the attenuation to the measurements of grain sizes should apply to Rayleigh area with limits to forms: $\lambda > 2\pi\bar{D}$, where λ is the wave length and $\bar{D}$ is the average grain size.

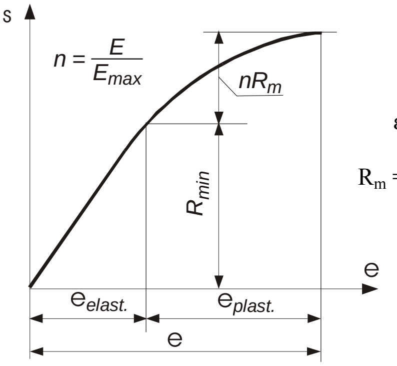
The research on ultrasonic wave attenuation (damping) and scattering [18, 24, 25] have shown the usefulness of the expression $\alpha = c\bar{D}^3\gamma^4$ for describing the scatter in Rayleigh area. The relevant literature on the question does not mention any adoption of Hall-Petch relationship for the assessment of mechanical properties of cast iron. The obstacles to this were the difficulties in determining the grain size of cast iron matrix and the presence of graphite precipitates.

Concept of utilising of the elongation curve for brittle material

An attempt to find a physical basis for the relation between tensile strength and the velocity of ultrasonic wave was also undertaken in paper [7]. Its author assumed, on the basis of elongation curve of a brittle material, that:

$$R_m = R_{\min} + nR_m \tag{4}$$

where: $R_{\min}$ - minimum tensile strength corresponding to the elastic strain range, n - fraction of tensile strength corresponding to the plastic strain range (Fig. 1).



$$\varepsilon_s = \varepsilon_{elast.} + \varepsilon_{plast.}$$

$$R_m = E / E_{\max} = (c_{L\max})^2$$

Fig. 1. Elongation curve for brittle material, where R_m is a minimum tensile strength corresponding to the elastic strain range $\varepsilon_{elast.}$, n is the fraction of tensile strength corresponding to the plastic strain range $\varepsilon_{palst.}$ [7]

Rearranging this assumed solution, we get:

$$R_m = \frac{R_{\min}}{1-n} \tag{5}$$

It was assumed that n may be determined from the quotient of the actual Young modulus (E) and hypothetical Young modulus ($E_{\max}$). As there is relation between the velocity of ultrasonic wave and Young modulus (if there is no change in density) the values of n were determined from the expression:

$$n = \frac{E}{E_{\max}} = \left(\frac{c_L}{c_{L\max}}\right)^2 \tag{6}$$

On substitution of formula (6) into (5), we get a relationship:

$$R_m = \frac{c_{L\max}^2 R_{\min}}{c_{L\max}^2 - c_L^2} = \frac{A}{B - c_L^2} \tag{7}$$

The values A and B are characteristic for cast iron. Despite rather controversial assumptions in paper [4] the obtained relationship was proven useful for the assessment of the tensile strength of grey cast iron.

Concept of utilizing of the law of mixtures

For their description of the relationship between material structure and its property, authors of many papers employed the co-called law of mixtures", defined as:

$$W = W_\alpha V_{V\alpha} + W_\beta V_{V\beta}\ ;\ V_{V\alpha} + V_{V\beta} = 1 \tag{8}$$

where: W - property of material, W_α, W_β - properties of α- and β-phases, respectively, $V_{V\alpha}$ $V_{V\beta}$, - volume fractions of α- and β-phases, respectively.

The law is derived from basic relations in stereology. Those relationships can be formulated as follows: a fraction of the length of unitary section corresponding to flat cross-sections of grains of a tested phase (l_α /l), fraction of surface occupied by this phase on the plane occupied by this phase on a unitary area of polished microsection (a_α /a), and a fraction of volume occupied by specific phase in the unit of alloy volume (V_α /V), are expressed by the same quantity.

$$\frac{l_\alpha}{l}=\frac{a_\alpha}{a}=\frac{v_\alpha}{v}=V_\alpha \qquad (9)$$

The law of mixtures is most often used for the description of relations in two-phase materials. Sometimes, to make the description more precise, a correction to the formula (8) should be introduced. For example in testing of tensile strength of two-phase titanium alloys [26] the description takes also into account the elastic and plastic interaction between α and β phases. It appeared that its value depends on the structure and may be either positive or negative or equal to zero. Cast iron is a structurally complex casting material and, it appears to require a scientific determination of the structural condition of its metallic matrix, as well as the analysis of complex stereology of its spheroidal graphite. In the first approximation it may be treated as material containing matrix and graphite precipitates. Even in such approach, the application of the law of mixtures for the description of properties of this material is rather difficult because it requires definition of the fraction of metallic material in the sample section. Tōru Ishino and Toshio Shiota [27], and then a number of other researches [28-31], were using for this purpose a concept of basic coefficient of the effective area fraction of the matrix A_{ef}. In their considerations on A_{ef} coefficient, the authors of the paper [29] analysed the layer of material of thickness d and a unitary length. In this layer they have modelled in various directions graphite precipitates in the shape of discs of diameter d and thickness t and spheroides of dia. d. Based on this model, they have found that A_{ef} in grey cast iron depended on the quotient of plate diameter and thickness, as well as their number while, in case of spheroidal iron, only on the quantity of graphite precipitates. In paper [32] on the other hand, the effective area fraction of matrix is expressed as a function of tensile strength.

The research performed by the author (*of the present paper*) shows that tensile strength, velocity of ultrasonic wave and the attenuation coefficient of the longitudinal ultrasonic wave in non-alloyed spheroidal cast iron depend on the volume fraction of pearlite, graphite shape factor, volume fraction of graphite and the quantity of graphite precipitates. Similar, as strong effect of the volume fraction of pearlite and that of the graphite shape factor makes difficult a simultaneous analysis of the effect of those variables on the above mentioned material properties. Therefore, it seems reasonable to introduce to the description of analysed property of a material (performed on the basis the law of mixtures) a coefficient which takes account of the structure of metallic matrix and a correction factor for the graphite stereology. Utilising the general idea of the coefficient of the effective area fraction of the matrix, a coefficient of pearlite fraction in the matrix, t, was defined. The meaning of pearlite fraction in the matrix is clarified in Fig. 2.

Using the law of mixtures and following the Thihiko Abe and Katsuya Ikawa [29], the general expression for the description of properties of material containing a two-phase matrix (ferrite and pearlite) as well as graphite shall have the following form:

$$W = W_m A_{ef} + W_G(1–A_{ef}) = [W_F(1\text{-}t)+W_p]A_{ef}+W_G(1–A_{ef}) \qquad (10)$$

where: W_m - property of matrix, W_F - property of ferrite. W_p - property of pearlite, W_G - property of graphite, A_{ef} - effective area fraction of matrix, t - coefficient of pearlite fraction in the matrix.

$A_{ef} = 1\text{-}V_{VG} / 100$

V_{VG} is the relative volume of pearlite mm^3/mm^3

$t = \frac{V_{VP}}{100} : A_{ef}$

V_{VP} is the relative volume of graphite mm^3/mm^3

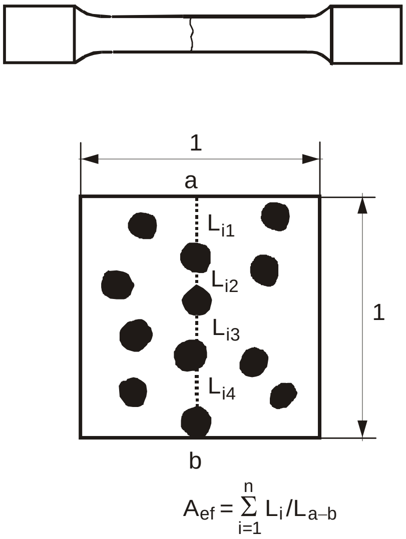


Fig.2. Meaning of pearlite fraction coefficient in the matrix

With the use of this expression, an attempt of substantiation for building relationships between ultrasonic inspection indicators and tensile strength was undertaken on the basis of the results of structural analysis, the research on mechanical properties and ultrasonic tests of the group of non-alloyed spheroidal cast iron. The evaluation of the usefulness of the equation (10) was performed for a group of nonalloyed spheroidal cast iron with varying contents of Si (2-3%) and manganese (0,1- 1%). This cast iron was obtained from cupola of dia. 1000 mm. Spheroidization was conducted in 900 kg ladie, with MgSi and MgCu used as master alloys. Modification was performed with ferrosilicon, Si75T. Various contents of silicon and manganese were obtained by using iron alloys, FeSi75T and FeMn6O, in the charge. The cast iron was poured over plate castings 25, 50 and 100 mm thick. Samples for the evaluation of tensile strength, for metallographic and ultrasonic examination, were taken from those plate castings. Quantitative structural analysis was performed on a comprehensive image analyser, Quantimet 720. Analysed parameters were: graphite shape factor, S_s, defined as a ratio of surface area and the square of graphite precipitate circumference, volume fraction of pearlite precipitates in a unit volume of the alloy V_{VP} (mm^3/mm^3), volume fraction of graphite precipitates in a unit volume of the alloy V_{VG} (mm^3/mm_3), average number of graphite grains per unit surface N_A (mm^{-2}). Five hundred graphite particles in random chosen fields were analysed on each sample. Particles having diameters above 10 μm were subject to analysis. Measurements of V_{VP}, V_{VG}, and N_A were performed on ten randomly chosen fields of the area 0.95 min^2. The length of projected secant was 688 mm.

Application of the law of mixtures and effective area fraction of matrix and the pearlite fraction in matrix for the valuation of tensile strength in the group of nonalloyed spheroidal cast iron

In order to determine a functional form of the equation (10) the tensile strength of ferrite, pearlite and graphite should be known. The literature [33] specifies $R_{m(F)}$ = 280-340 MPa, $R_{m(p)}$ = 700-800 MPa and $R_{m(G)}$ = 20 MPa, respectively, thus showing a significant scatter of those values. On the other hand, it should be kept in mind that the tensile strength shall depend, among others, on the process, liquid metal preparation, melting furnace, chemical composition of cast iron and the conditions of alloy crystallisation. The other fact to be remembered is that magnesium content and, consequently, the shape of graphite in cast iron drawn from ladle vary with time. Also, few founders take into account the presence of significant level of impurities and impoverishment in magnesium of the first portion of cast iron drawn from the ladle. Still other factor to be considered is the differentiation of magnesium content and therefore of the shape of graphite in thin and thick walls of a casting due to different solidification times. All those elements are characteristic for specific foundry and have significant effect on the properties of cast iron castings. That is why, in order to take them into account, the evaluation of tensile strength of the structural components of the matrix should be carried out in the material produced in a specific foundry. For such evaluation the samples are to be taken from cast iron with ferritic and pearlitic matrix. To evaluate the actual $R_{m(F)}$ and $R_{m(P)}$, samples were picked from cast irons with ferritic and pearlitic matrix. For the sample with ferritic matrix exhibiting R_m = 444 MPa and A_{ef} = 0.931, the $R_{m(F)}$ = 477 MPa, while for a sample with pearlitic matrix exhibiting R_m = 570 MPa and A_{ef} = 0.939, the $R_{m(P)}$ = 607 MPa. For graphite, the literature data, R_m = 20 MPa, were taken. Upon substituting those value in the general relationship (10) the following form is obtained:

$$R_m = (457 + 130\,t)A_{ef} + 20 \qquad (11)$$

This equation enables evaluation of tensile strength in analysed group of cast iron while observing the tests of statistical estimation: Y = 9, S = 476, R = 0.96, F = 319, α = 0.01, which confirm sufficient accuracy and reliability of the proposed description.

Structural model for the substantiation of the relationships between the velocity of longitudinal ultrasonic wave and tensile strength

The velocity of longitudinal ultrasonic wave is affected by the volume fractions of structural constituents in the unit volume of the alloy, graphite shape factor, as well as the average number of graphite grains per unit surface area of the alloy. In order to take the graphite shape factor and average number of graphite grains into account in the model, a corrective coefficient has been successfully introduced to correct the effect of the deviation of graphite shape from spherical and the deviations of the average number of graphite grains from average number of graphite grains in standard sample. The shape factor for circle S_s = 0.0795. The average number of graphite grains in standard samples was $N_{AW} \approx 104$. Thus the coefficient covering the effect of the deviation of the average number of graphite grains from average number of graphite grains in standard sample and the deviations of graphite shape from spherical has a form: $z = (N_A{:}N_{AW})(S_s{:}0{,}0795)$. After introducing this corrective coefficient in the general equation the velocity of the longitudinal ultrasonic wave may be evaluated on the basis of the expression:

$$c = c_{osn.}A_{ef} + c_G(1-A_{ef})z = [c_F(1-t) + c_P\,t\,]A_{ef} + c_G(1-A_{ef})\,z \qquad (12)$$

where: c - the velocity of longitudinal ultrasonic wave, m/s, z - the coefficient covering the effect of the deviation of the average number of graphite grains from average number of graphite grains in standard samples and the deviations of graphite shape from spherical.

In order to determine the functional form of this equation the velocity of ultrasonic wave propagation in ferrite, pearlite and graphite must first be known. Since the velocity of the longitudinal ultrasonic wave depends on many factors related to casting manufacture, it is best to determine it for material obtained in established production conditions. It should also be remembered that cast irons of similar structure and mechanical properties but a different history (raw condition or after heat treatment) are not equivalent in ultrasonic terms. The evaluation of the usability of the equation was performed for the same group which the tensile strength was evaluated. The material was analysed in raw condition. For the sample with ferritic matrix showing c_L = 5687 m/s and A_{ef} = 0.931 the $c_{L(F)}$ = 6108 m/s, while for the sample with pearlitic matrix showing c_L = 5751 m/s and A_{ef} = 0.939 the $c_{L(P)}$ = 6124 m/s. For graphite the $c_{L(G)}$ = 2000 m/s. Upon substituting those values in the relation (12), we get the functional form of the equation:

$$c_L = (6108 + 16t - 2000z)A_{ef} + 2000z \qquad (13)$$

In order to determine the relation between tensile strength and the velocity of longitudinal ultrasonic wave propagation in the presented structural model, we analysed the function:

$$A_{efC_L} = \frac{c_L - 2000z}{(6108 + 16t - 200z)} \qquad (14)$$

$$A_{efc_L} \in (0,1); \qquad t \in \langle 0,1 \ \rangle \qquad 6108 + 16t - 2000z \neq 0$$

$$16t \neq 200\,z - 6108$$

The function $c_L(A_{ef})$ is ascending one because (6108 + 16t - 2000z) > 0. The relation between R_m and c_L is correct for $c_L \in$ (6108 + 16t - 2000z). Utilising of relation (11) and effective coefficient of the matrix, A_{efc_L} for strength calculations enabled the determination of tensile strength using statistical estimation tests: Y = 9, S = 476, R = O.96, F = 316, α = 0,01, which confirm sufficient accuracy and reliability of the proposed description. A comparison of tensile strength results obtained from experience with those from calculation is presented in Figure 3.

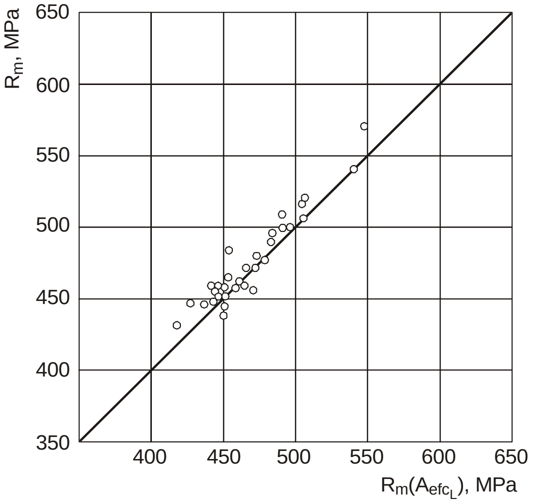


Fig. 3. Comparison of tensile strength results obtained from measurement and those calculated in accordance with model equation $R_m = f(A_{efc_L})$

Structural model for the substantiation of the relation between the attenuation coefficient of the longitudinal ultrasonic wave and tensile strength

The attenuation coefficient of the longitudinal ultrasonic wave is affected by volume fractions of structural constituents in a unit volume of the alloy, graphite shape factor, as well as the average number graphite grains per unit area of the alloy. In order to take into account the effects of graphite shape factor and average number graphite grains on the value of the attenuation coefficient of the longitudinal ultrasonic wave, a corrective coefficient was introduced to correct the effect of the deviation of graphite shape from spherical and the deviations of the average number of graphite grains from average number of graphite grains in standard samples. This coefficient is defined by the equation $z = (N_A : N_{AW})(S_s : 0.0795)$. Once this coefficient is introduced to general equation, the attenuation coefficient of the longitudinal ultrasonic wave can be determined on the basis of:

$$\alpha = \alpha_{osn.}A_{ef} + \alpha_G(1-A_{ef})z = [\alpha_F(1-t) + \alpha_P t]A_{ef} + \alpha_G(1-A_{ef})z \qquad (15)$$

where: α - the attenuation coefficient of the longitudinal ultrasonic wave, dB/mm,z - the coefficient covering the effect of the deviation of the average number of graphite grains from average number of graphite grains in standard samples and the deviations of graphite shape from spherical.

In order to determine the functional form of this equation the values of attenuation coefficient of the longitudinal ultrasonic wave in ferrite, pearlite and graphite of tested cast-iron group must first be known. Such evaluation has been performed on samples with ferritic and pearlitic matrices. For the sample with ferritic matrix indicating $\alpha = 0.18$ dB/mm and $A_{ef} = 0.934$ the $\alpha_F = 0.193$ dB/mm, while for the sample with nearly pearlitic matrix indicating $\alpha = 0,05$ dB/mm and $A_{ef} = 0.053$ the $\alpha_P = 0,053$ dB/mm. For graphite, the $\alpha_G = 1$ dB/mm was assumed. After substituting those values in the relation (15), we get the functional form of the equation:

$$\alpha = (0.193 - 0.140t - z)A_{ef} + z \qquad (16)$$

In order to determine a relationship between tensile strength and the value of attenuation of the longitudinal ultrasonic wave in the presented structural model, we analysed the function:

$$A_{ef\alpha} = \frac{\alpha - z}{(0.103 - 0.140t - z)} \qquad (17)$$

$$A_{ef\alpha} \in (0,1); \qquad t \in \langle 0,1 \rangle \qquad 0,193 - 0.140t - z \neq 0$$

The α (A_{ef}) is decreasing function. The relationship between R_m and α is correct for $\alpha \in (0.193 - 0.140t - z)$. Utilising of relation (11) and effective coefficient of the matrix, $A_{ef\alpha}$ for strength calculations enabled the determination of tensile strength using statistical estimation tests: Y = 8, S = 476, R = 0.97, F = 438, α = 0.01. A comparison of tensile strength results obtained from experience with those from calculation is presented in Figure 4.

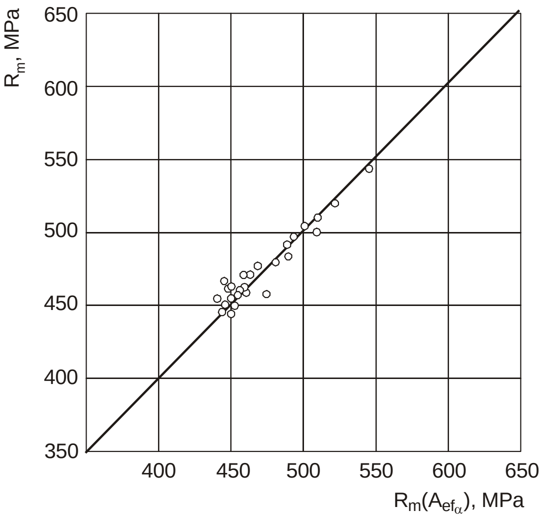


Fig. 4. Comparison of tensile strength results obtained from measurement and those calculated in accordance with model equation $R_m = f(A_{ef\alpha})$.

3. Conclusions

The above presented elaboration seems to provide adequate substantiation for formulating relationships between ultrasonic inspection indication and mechanical properties.

References

[1] R. Ziegler, R. Gerstner: Die Schallgeschwindigkeit als kemizeichende Gröβe für die Beurteilung von Gussein, Giesserei H. 3, 185-193 (1958).

[2] J. Koppe1mam, R. Frielinghaus.: Die Bedeutung der Ultraschallmesstechnik für die Gefügebeurteilung von Eisenwerkstoffen, insbesondere Gusseisen. Giesserei H. 24, 802-809 (1966).

[3] W. Weis, M. Lampic, K. Orths: Untersuchungen über die Prüfbarkeit von Gusseisen mit Lamellengraphit mittels Ultraschall. Giessereiforschung H. 1, 1-11 (1975).

[4] W. Lenard: Badanie wytrzymałości na rozciąganie żeliwa szarego w odlewie metodą ultradźwiękową. Przegląd Odlewnictwa, Nr 2, 37-39 (1978).

[5] D. Pohl, A. Aalen: Qua1itätssicherung mittels Ultraschall bei der Herstellung von Gusseisen mit Kugelgraphit. Giesserei Nr 19. (Mitteilung aus dem Werkstoffkunde Institut der Schwäbischen Hüttenwerke GmbH Wasseralfingen).

[6] S. Kipka, T. Ankofer: Ermittlung der Ferstigkeit an sphärolitischem Gusseisen mit Hilfe der Ultraschall-geschwindigkeit. Giesseitechnik H3, 84-85 (1981).

[7] Z. Pawłowski: Bewerhing der Gusseisenfestigeit mittels Ultraschallmessungen. Giessereitechnik H. 3, 8 i-85 (1982).

[8] Yoshiaki Sano, Shigeki Moriyama: Evaluation of the quality of the grey iron casting material by ultrasonic testing. Imono. Nr 6, 364-3 70 (1982).

[9] Hidehiko Kage, Yuichi Tanaka: Evaluation of cast iron quality by ultrasonic testing. Imono, Nr 7, 408-4 14 (1984).

[10] Taku Ohide, Junihi Mita, Katsuma Ikawa: Relationship between mechanical properties and ultrasonic velocity of cast iron. Imono, Nr 2, 261-267 (1986).

[11] A. Topuz, E. Topcu, A. Bakkaloĝlu, M. Marsoglu: Ultra-schaligefüge - untersuchungen von zwischenstufenvergütetem sphäroguss. Praktische Metalographic, Nr 6, 278-287 (1997).

[12] J. Deputat: Zastosowanie pomiarów prędkości i tłumienia fali ultradźwiękowych. XIII Krajowa Konferencja Badań Nieniszczących. Referat 2.

[13] D. Aurich, E. Martin: Prerequisites possibilities and limitations of grain size determination by ultrasonic attenuation measurement. Arch. Eisenüten. No 3, (1970).

[14] R. Klimnan, G. R. Webster, F. J. Marsch. E. T. Stephenson: Ultrasonic prediction of grain size, strength and toughness plain carbon steel. Materials Evaluation, No 10, 26-32 (1980).

[15] R. Klinman, E. T. Stephenson: Ultrasonic prediction of grain size and mechanical properties of plain carbon steel. Materials Evaluation, No 11, 1116-1120 (1981).

[16] F. Nadeau, J. F. Bussiere. G. Van Drunen: On the relation between ultrasonic attenuation and fracture toughness in type 403 stainless steel. Materials Evaluation, No 43, 101-104 (1985).

[17] J. F. Bussiere: On line measurement of the microstructure and mechanical properties of steel Materials Evaluation, No 4, 560-567 (1986).

18] E. Papadakis: Ultrasonic attenuation caused by scattering in polycrystalline metals. J. Acoust. Soc. Am, No 4, 711-717 (1965).

[19] E. P. Papadakis: Ultrasonic attenuation an velocity on SAE 51200 steel quenched from various temperatures. Met. Trans., No 1, 1053-1055 (1970).

[20] R. Kettler: Surface ultrasonic measurement of grain size of silicon iron sheet. Met. Trans., No 5, 952-954 (1974).

[21] E. P. Papadakis: Ultrasonic nondestructive test for the detection of improver head treatment of steel. Materials Evaluation, No 3, 136-14 1 (1965).

[22] S. Matsurnoto, R. Klimura: The relation between grain size and ultrasonic attenuation coefficient in austenitic stainless steel and irons. Trans. Nat. Inst. Metals., No 4, 21-27 (1972).

[23] G. Bott: Utilization of the ultrasonic attenuation measuring method to sort out normalized and not annealed sheets. Materialprüfung, No 7, 251-258 (1977).

[24] B. Fay: Determination of the grain size of steel using the ultrasonic backscatter method. Arch. Eisenhütenwerke, No 2, 119-126(1976).

[25] K. Goebbels: Evaluation of steel structure with scattered ultrasonic pulse. Materialprüfung, No 7, 231-236 (1975).

[26] S. Anken, H. Margolin: A rationalization of stress-strain behaviour of two-ductile phase alloys. Metallurgical Transactions A., No 12, 1986-2209 (1985).

[27] Töru Ishino, Toshio Shiota: Some considerations on the facture mechanism and strength of cast irons. Imono, No 7, 663-669 (1964).

[28] Toshio Shiota, Shinichiro Komatsu: Relation between the effective sectional area and the static strength of cast iron. Imono, No 10, 602-607 (1977).

[29] Toshihiko Abe, Katsuya Ikawa: Estimation of velocity tensile strength and damping capacity of cast iron with effective area fraction model. Imono, No 6, 479- 484 (1985).

[30] Toshihiko Abe, Katsuya Ikawa: Effect of voids on density and sound velocity of cast iron. Imono, No 2 116-122 (1986).

[31] Toshihiko Abe, Shang Zhung Wang, Katsuya Ikawa: Effect of stress and strain on ultrasonic sound velocity in cast iron. Imono, No 10, 629-635 (1985).

[32] Toshihiko Abe, Shang Zhung Wang, Katsuya Ikawa: Effect of structure and mechanical properties on the sound velocity in cast iron. Imono, No 6, 351-357 (1985).

[33] F. Staub, J. Adamczyk, J. Gubała, A. Maciejny: Metaloznawstwo. Wyd. Śląsk, Katowice (1977).