Quality Control by Means of Ultrasonic in the Production of Ductile Iron

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The paper presents several concepts of physical substantiation for the rationale of building the relationships between mechanical properties and ultrasonic inspection indicators. Special emphasis is put on assessing the influence of graphite shape number $S_S$ and the number of graphite precipitations $N_A$ on the tensile strength and longitudinal ultrasound wave velocity of ductile iron manufactured under production conditions. Tests were conducted on wedge casts which were used as samples for tensile tests and a map of the structure and longitudinal ultrasound wave velocity was determined for the cast wedges. The tensile tests were conducted and values of graphite shape number, average number of graphite precipitations and longitudinal wave velocity were determined in the place where the sample was broken. Relations between the mechanical properties, graphite shape number, number of graphite precipitations and the velocity of longitudinal ultrasonic wave were determined.

KEY WORDS: ductile iron; ultrasonic method; shape and number of graphite precipitations; mechanical properties.

1. Introduction

Attempts were made at providing substantiation for the rationale of building relationships between tensile strength and ultrasonic inspection parameter. In the research on developing cast-iron quality-inspection techniques there is a noticeable tendency towards evaluating its mechanical properties and structure on the basis of ultrasonic measurements. The usual objection raised to the relationships between tensile strength and ultrasonic wave velocity and attenuation, reported in the literature, is that those relationships are empirical and have no physical substantiation.

Concept of Utilizing the Existence of Interatomic Forces

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

$$F = \beta \Delta r + \gamma \Delta r^2$$

where: $\beta, \gamma$ are constants for specific type of atoms, $\Delta r$, 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, $\Delta r$, is thus modified to:

$$F = \beta \Delta r$$

A simplified relation reflects a linear relationship between the force, $F$, and the elongation, $\Delta r$, 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 $\sigma = (\beta \rho c)$. In this expression $E = \beta \rho c$ is the Young modulus. For brittle materials the yield point corresponds to the immediate tensile strength. If we put a 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:

$$Y_S = \frac{\beta}{r_o} \frac{\Delta r_{\text{max}}}{r_o} \frac{0.5 \rho c^4}{r_o}$$

where: $\rho$, 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 the 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 of Utilizing the Elongation Curve for Brittle Material

An attempt to find a physical basis for the relation be-
tween tensile strength and the velocity of ultrasonic wave was also undertaken in the paper.9 On the basis of the elongation curve of a brittle material, the author assumed that:

\[ \text{UTS} = \text{UTS}_{\text{min}} + n\text{UTS} \] ..........................(4)

where: \( \text{UTS}_{\text{min}} \) minimum tensile strength corresponding to the elastic strain range; \( n \), fraction of tensile strength corresponding to the plastic strain range (Fig. 1).

Rearranging this assumed solution, we get:

\[ \text{UTS} = \frac{\text{UTS}_{\text{min}}}{1 - n} \] ..........................(5)

It was assumed that \( n \) may be determined from the quotient of the actual Young modulus \((E)\) and hypothetical Young modulus \((E_m)\). As there is a 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:

\[ n = \frac{E}{E_m} = \left( \frac{c_L}{c_{L_{\text{max}}}} \right)^2 \] ..........................(6)

where: \( c_L \) is longitudinal ultrasonic wave velocity, \( c_{L_{\text{max}}} \) is maximum ultrasonic wave velocity.

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

\[ \text{UTS} = \frac{c_{L_{\text{max}}}}{c_{L_{\text{min}}}} \cdot \text{UTS}_{\text{min}} = \frac{A}{B} \] ..........................(7)

The values \( A \) and \( B \) are characteristic for cast iron. Despite rather controversial assumptions in the paper9 the obtained relationship was proven to be useful for the assessment of the tensile strength of grey cast iron.

**Concept of Utilizing 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:

\[ W=W_aV_{\alpha a}+W_\beta V_{\beta}\quad V_{\alpha a}+V_{\beta}=1 \] ..........................(8)

where: \( W \), property of material; \( W_a \), \( W_\beta \), properties of \( \alpha \)- and \( \beta \)-phases, respectively; \( V_{\alpha a} \), \( V_{\beta} \), volume fractions of \( \alpha \)- and \( \beta \)-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 \((l/1)\), fraction of surface occupied by this phase on the plane occupied by this phase on a unitary area of polished microsection \((a_\alpha/a)\), and a fraction of volume occupied by a specific phase in the unit of alloy volume \((V_\alpha/V)\) are expressed by the same quantity.

\[ \frac{l_\alpha}{l} = \frac{a_\alpha}{a} = \frac{V_\alpha}{V} = \frac{V_a}{V} \] ..........................(9)

The law of mixtures is most often used for describing 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 the tensile strength of two-phase titanium alloys23 the description also takes into account the elastic and plastic interaction between \( \alpha \) and \( \beta \) 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 analysis of the complex stereology of its spheroidal graphite. In the first approximation it may be treated as material containing matrix and graphite precipitates. Even in such an approach, applying the law of mixtures for describing the properties of this material is rather difficult because it requires definition of the fraction of metallic material in the sample section. Ishino and Shiota24,25 and then Abe et al.26-29 used for this purpose a concept of a basic coefficient of the effective area fraction of the matrix \( A_{\text{eff}} \). In their considerations on \( A_{\text{eff}} \), coefficient, the authors of the paper29 analysed the layer of material of thickness and a unitary length. In this layer they modeled in various directions graphite precipitates in the shape of discs of diameter and thickness and spheroids of diameter. Based on this model, they found that \( A_{\text{eff}} \) in gray 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 paper29 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 ductile iron depend on the volume fraction of pearlite, graphite shape factor, volume fraction of graphite and the quantity of graphite precipitates. Likewise, the strong effect of the volume fraction of pearlite and that of the graphite shape factor makes a simultaneous analysis of the effect of those variables on the above mentioned material properties difficult. 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. Utilizing the general idea of the coeffi-
cient of the effective area fraction of the matrix (Fig. 2), a coefficient of pearlite fraction in the matrix, \( t \), was defined.

Using the law of mixtures and following Abe and Ikawa\(^{26} \), 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:

\[
W = W_m A_{ef} + W_G (1 - A_{ef}) = (W_F (1 - t) + W_P t) A_{ef} + W_G (1 - A_{ef})
\]

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,

\[
A_{ef} = 1 - V_G / 100
\]

\( V_G \) is the relative volume of graphite \( \text{mm}^3/\text{mm}^3 \),

\[
t = \frac{V_{VP}}{100} \cdot A_{ef}
\]

\( V_{VP} \) is the relative volume of pearlite \( \text{mm}^3/\text{mm}^3 \).

In order to determine a functional form of the Eq. (10) the tensile strength of ferrite, pearlite and graphite should be known. The literature\(^{30} \) specifies \( UTS_{F} = 280-340 \) MPa, \( UTS_{P} = 700-800 \) MPa and \( UTS_{G} = 20 \) MPa, respectively, thus showing a significant scatter of those values. On the other hand, it should be borne in mind that the tensile strength shall depend, among other things, on the process, liquid metal preparation, melting furnace, chemical composition of cast iron and the conditions of alloy crystallization. The other fact to be remembered is that magnesium content and, consequently, the shape of graphite in cast iron drawn from a ladle vary with time. Also, few founders take into account the presence of a significant level of impurities and impoverishment in magnesium of the first portion of cast iron drawn from the ladle. Yet 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 a specific foundry and have a significant effect on the properties of cast iron castings. That is why, in order to take them into account, evaluation of the tensile strength of the structural components of the matrix should be carried out in the material produced in a specific foundry.

**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 introduced to correct the effect of the deviation of the graphite shape from the spherical and the deviations of the average number of graphite grains from the average number of graphite grains in a standard sample. The shape factor for circle \( S_s = 0.795 \). The average number of graphite grains in standard samples was \( N_{GW} \). Thus the coefficient covering the effect of the deviation of the average number of graphite grains from average number of graphite grains in a standard sample and the deviations of the graphite shape from the spherical has the form:

\[
z = (N_s : N_{GW}) (S_s : 0.795)
\]

Introducing this corrective coefficient in the general equation the velocity of the longitudinal ultrasonic wave may be evaluated on the basis of the expression:

\[
c = c_{can} A_{ef} + c_G (1 - A_{ef}) z = [c_F (1 - t) + c_P t] A_{ef} + c_G (1 - A_{ef}) z
\]

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 the average number of graphite grains in standard samples and the deviations of the graphite shape from the 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.

**Cast Iron Quality Evaluation**

The basis for the acceptance of iron castings is their microstructure and mechanical properties usually determined on the material of separately cast test wedges. Such evaluation boils down to performing metallurgical tests and a tensile strength test. The testing is costly and time-consuming. It often happens in industrial practice that the decision about sending the castings to a customer or for mechanical working or thermal treatment has to be made before the results are available. Wrong decisions result in additional costs for the foundry. Therefore, the developments permitting rapid non-destructive evaluation of the structure and mechanical characteristics of tested material acquire great importance.

Such evaluation may be performed directly on the casting. For this purpose a nomogram for the evaluation of mechanical properties from ultrasonic measurements and an...
atlas of test-sample structures after ultrasonic testing should be developed, the measurement locations for each casting design (preferably as early as the casting design phase) should be defined and the wave velocity ranges for approved and rejected castings determined. The diagram of procedure for developing the nomogram shown in Fig. 3 (below) should be determined.

The diagram of preparation of the nomogram for the ultrasonic evaluation of casting quality, as shown in Fig. 3, is based on a casting of a wedge. The same diagram of procedure shall be required for developing a nomogram for a specific casting wall. It is important that the casting from which the tensile–strength test piece will be made is subject to thorough ultrasonic evaluation in order to ascertain the distribution of the ultrasonic wave velocity value along the whole measured length of test pieces. This enables subsequent determination of the wave velocity for the area in which a rupture has occurred. Determination of the velocity value and respective tensile strength value in this manner serves in building the diagram of UTS\( = f(c_v)\). If observation of the test-piece surface in the rupture area/location indicates a presence of slugging, gassing or porosity, the result of such measurement shall be rejected. It is not recommended to utilize the results of the evaluation of wave velocity on test-piece material after its rupture, while drawing of conclusions about the strength from velocity measurements in the rupture area is completely unacceptable because its density changes as it becomes deformed. Figure 4 presents changes in cast-iron density in the measured area of a test piece after resistance tests.\(^{27}\)

2. Experimental Procedure

The tests were conducted on 19 cast iron melts of the following composition: 3.5–3.8% C, 2.5–2.8% Si, 0.40% Mn, max. 0.07% P, max. 0.023% S, 0.2–0.3% Cu, max. 0.06% Cr, 0.038–0.050% Mg. The alloy was prepared in a induction furnace PIT 1.6.

Spheroidisation and modification of the cast iron were conducted with the FeSiMg9 master alloy in the KOZ-Q-2Mg ladle with crucible top. To determine the influence of the filling time on the ceasing of the spheroidisation effect, and thus the change of graphite precipitation shape, the wedge forms were filled after different times of keeping the liquid alloy in the pouring ladle.

The feeding elements of the castings were rejected and plates were obtained for testing the structure and ultrasonic wave velocities (Fig. 5). The plate surfaces were milled to have the opposite surface parallel. This operation was conducted to prepare the plates for ultrasonic tests (Fig. 6). Velocity of the longitudinal ultrasound wave was measured by applying the head in the points between point A and point B.

Velocities of the longitudinal ultrasound wave were measured with an Echometer 1073 VS with a head 10.4/6 PB 4. Samples for tensile testing were made from the plates after ultrasonic tests. Testing of ultimate tensile strength

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\(^{27}\) Distance

Fig. 3. Schematic presentation of the process of preparation of the nomogram for evaluating cast iron tensile strength on the basis of measurement of the velocity of the longitudinal ultrasonic wave.

Fig. 4. Variation of cast-iron density in the test-piece tensile rupture area.\(^ {27}\)

Fig. 5. Wedge casting for testing.
was conducted on UTS 250.4. After the tensile strength tests on the broken samples the position of the crack in the area between edge A and edge B was determined and indicated on the metallographic test plate. In these areas, longitudinal ultrasound wave velocity was assessed. Its value was identical here and in the corresponding areas of the ultrasound test plates. Out of the marked area of the metallographic test plate, samples were cut off for structural analyses.

The samples were polished with abrasive paper of a granularity of 150, 500 and 1 000. For finishing, a diamond suspension was used. The microstructure was observed on non-etched polished sections.

The quantitative structural analysis consisted in evaluating the shape index of graphite precipitation \( S_s \) (defined as a quotient of the surface area and the graphite precipitation square perimeter) and the average number of graphite precipitations per one surface unit \( N_A \). For each sample, 500 graphite precipitations at randomly selected fields were analysed. Particles larger than 10 \( \mu m \) were analysed. The measurement was conducted at 10 randomly selected fields.

![Fig. 6. Diagram of measurement of the longitudinal ultrasonic wave velocity in the plate where the sample for the tensile strength test was obtained.](image)

![Fig. 7. Distribution of the ultrasonic wave velocity \( c_L \) along the plate from which sample for tensile tests was taken: sample 12.](image)

![Fig. 8. Microstructure of samples in the area adjacent to the test-piece tensile rupture area; a) sample 12, b) sample 19. Non-etched polished sections, magn. \( \times300 \).](image)

### Table 1. Results of the quantitative microstructural analysis and longitudinal ultrasound wave velocity in the place where the sample was broken, as well as ultimate tensile strength.

<table>
<thead>
<tr>
<th>No.</th>
<th>UTS, MPa</th>
<th>Structural parameters</th>
<th>Longitudinal ultrasound wave velocity ( c_L ), m/s</th>
<th>Area rate of ferrite, %</th>
<th>Area rate of pearlite, %</th>
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<tr>
<td>1</td>
<td>486</td>
<td>0.063 139</td>
<td>5636</td>
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<tr>
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<td>5654</td>
<td>71.1</td>
<td>20.3</td>
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<tr>
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of a 0.15 mm² surface area for each sample.

3. Experimental Results

An example distribution of the longitudinal ultrasound wave velocities along the plates, from A to B (Fig. 6) has been presented in Fig. 7. Figure 8 shows an example microstructure of plate material from which samples for the tensile tests were made.

Results of tests of the longitudinal ultrasonic wave velocity $c_L$, graphite precipitation shape index $S_s$, number of graphite precipitation $N_A$ in the area of sample breaking, as well as the ultimate tensile strength UTS are presented in Table 1.

The relation between the ultrasonic wave velocity $c_L$ and the shape index of graphite precipitation $S_s$ has been presented in Fig. 9. The relation between the average number of graphite precipitation $N_A$ and the longitudinal ultrasonic wave velocity $c_L$ has been presented in Fig. 10.

The relation between the ultimate tensile strength UTS and the shape index of graphite precipitation $S_s$ has been presented in Fig. 11.

The relation between the ultimate tensile strength UTS and the average number of graphite precipitation $N_A$ has been presented in Fig. 12.

The relation between the ultimate tensile strength UTS and the longitudinal ultrasonic wave velocity $c_L$ has been presented in Fig. 13.

The results obtained are characteristic of the high values of the correlation coefficient, which suggests that they are useful for the needs of the foundry where the tests were conducted.

Formulas (12)–(16) form the basis of developing nomograms, which are going to be used in the non-destructive control of ductile iron casting diagnosis. An example nomogram has been presented in Figs. 14 and 15.

Fig. 9. Relation between the longitudinal ultrasonic wave velocity $c_L$ and the shape index of graphite precipitation $S_s$.

$$ c_L = 3511.5 S_s + 5415.3, \quad R = 0.99 $$

Fig. 10. Relation between the longitudinal ultrasonic wave velocity $c_L$ and the average number of graphite precipitations $N_A$.

$$ c_L = 0.4804 N_A + 5572.2, \quad R = 0.99 $$

Fig. 11. Relation between the ultimate tensile strength UTS and the shape index of graphite precipitation $S_s$.

$$ UTS = 4446.9 S_s + 207.83, \quad R = 0.99 $$

Fig. 12. Relation between the ultimate tensile strength UTS and the average number of graphite precipitations $N_A$.

$$ UTS = 0.6084 N_A + 406.23, \quad R = 0.99 $$

Fig. 13. Relation between the ultimate tensile strength UTS and the longitudinal ultrasonic wave velocity $c_L$.

$$ UTS = 1.2631 c_L - 6631.7, \quad R = 0.99 $$

Fig. 14. Nomogram for assessment of the shape index of graphite precipitation $S_s$ from the measurement of longitudinal ultrasonic wave velocity $c_L$. 

$$ UTS = 0.6084 N_A + 406.23, \quad R = 0.99 $$
4. Conclusions

It was found that in the ductile iron tested longitudinal ultrasonic wave velocity $c_L$ and ultimate tensile strength $UTS$ are in linear dependence with the graphite shape index $S_S$ and average number of graphite precipitations $N_A$ of the ductile iron.

Increase in their values is accompanied by an increase in the longitudinal ultrasonic wave velocity and ultimate tensile strength in tested ductile iron. This dependence is characteristic of a high correlation coefficient. This proves that it is possible to use it in practice.

Nomograms have been developed to assess the graphite shape index $S_S$, the average number of graphite precipitations $N_A$ and ultimate tensile strength $UTS$ from the longitudinal ultrasonic wave velocity $c_L$. These nomograms were used as a basis for acceptance at the non-destructive quality control of ductile iron castings in the condition of the foundry for which the tests were conducted.

REFERENCES

4) S. Areste: 8 World Conf. on NDT, Cannes, (1976), IC10.