

Application of ultrasound in testing of heat-treated cast iron

A.W. Orłowicz^{a,*}, M. Mróz^a, A. Trytek^a

^aDepartment of Casting and Welding Technical University of Rzeszów, ul. Wincentego Pola 2, 35-959 Rzeszów, Poland
* e-mail: zois@prz.edu.pl

Received on 15.01.2007; Approved for print on: 20.02.2007

Summary

The paper is an attempt to clarify the effect of heat treatment on the cast iron structure and propagation of ultrasonic waves in it with the objective of showing the usability of this technique for diagnosis of heat treatment effects.

Key words: ultrasonic testing, heat-treated, cast iron, structure.

1. Introduction

The first papers concerning ultrasonic diagnosis of the mechanical properties of cast iron were published in the 1950-ties [1,2]. From this time on many works that concerned the relationships between structure, mechanical properties and the acoustic parameters of material were carried out and published. Most research was devoted to gray iron [2-13]. These researches concerned mainly the as-cast material. For technical reasons it is easiest to assess the speed of longitudinal ultrasonic waves, c_L . Therefore, most of the works relate to this acoustic parameter of cast iron.

2. Tests on heat treated cast iron

Few papers in the technical literature deal with the effect of heat treatment on the speed of longitudinal ultrasonic waves in cast iron. Papers [14,15] report that samples of spheroidal cast iron after graphitizing, normalizing, quenching or toughening (quenching and tempering) exhibit lower values of c_L , compared to as-cast material. The author of the paper [16] has showed that the chemical composition and heating temperature has effect on the speed of longitudinal ultrasonic wave of samples cooled in air. Findings in paper [17] are that the c_L decreases with rising temperature and time of austenitizing in cast iron hardening

process. The extending of tempering time favors also the reduction of the speed of longitudinal ultrasonic wave. According to the author of paper [18] the rise of the austenitizing temperature of spheroidal cast iron is accompanied by the reduction in the value of c_L . On the other hand the rising temperature of isothermal holding during hardening with isothermal transformation is accompanied by the rise in the value of c_L [19].

These papers show that the ultrasonic wave speed measurements may be useful for the inspection of properties of heat treated castings. The practice shows that the relationships between the tensile strength and the speed of the ultrasonic wave developed for as-cast iron are not equivalent to those for the same iron after heat treatment. Poor understanding of this is frequently the cause of lack of confidence in the diagnosis of cast iron structure and mechanical properties by ultrasonic method.

3. Propagation of ultrasonic waves in castings with different structures

In case of such structurally complex casting material as the cast iron, the structure of an alloy in as-cast condition makes the evaluation of acoustic signal of the propagated ultrasonic wave much more difficult. Both the graphite precipitate form, shape, distribution, size and the matrix structure, which undergoes

changes in the process of making castings of different thickness, contribute to the difficulty.

For a homogeneous material, the longitudinal wave speed c_L in solids depends on the Young's modulus E and material density ρ as with ν being the Poisson ratio.

$$c_L = \sqrt{\frac{E(1-\nu)}{\rho(1+\nu)(1-2\nu)}} \quad (1)$$

It was found that, under the assumption of validity of relationship (1), the velocity of ultrasonic wave depends also (according to the mixing law (2)) on volume fractions of individual structural components;

$$c_L = c_{L(\text{matrix})} V_{V(\text{matrix})} + c_{L(\text{graphite})} V_{V(\text{graphite})} \quad (2)$$

where: $c_{L(\text{matrix})}$, $c_{L(\text{graphite})}$ – longitudinal ultrasonic wave velocities in matrix and graphite, respectively, $V_{V(\text{matrix})}$, $V_{V(\text{graphite})}$ – volume fraction in matrix and graphite respectively

The research on cast iron has shown that, provided the relationship (1) is right, the velocity of longitudinal ultrasonic wave depends also on the volumetric share of structure components and on stereological parameters of graphite [20] as illustrated in Figure 1.

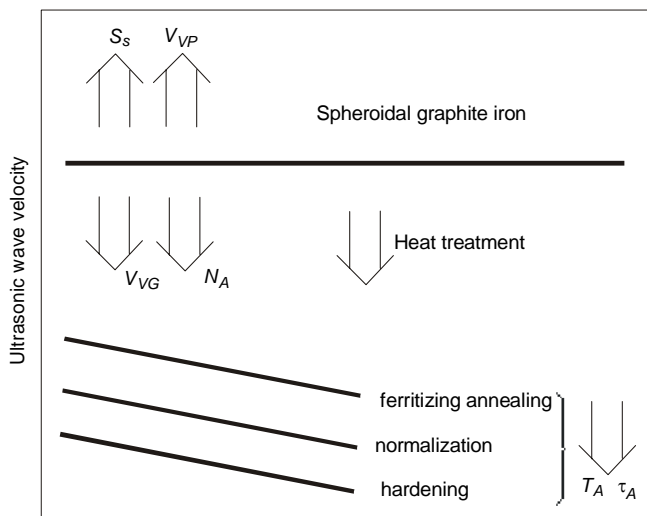


Fig. 1. The effect of cast iron volume (fraction of pearlite V_{VP} , volume fraction of graphite V_{VG} , graphite shape factor S_s , quantity of graphite precipitates N_A , austenitizing time and temperature (T_A , τ_A) and the type heat treatment on the velocity of ultrasonic wave

Besides, the wave velocity depends on the average grain size of material and grain orientation [21]. In the area of individual grains the velocity of ultrasonic wave will not be the same because the modulus E has different values depending on the crystallographic plane. Ultrasonic wave transition from a zone of one value of the modulus E to the zone with its other value involves a deflection, dispersion and reflection at the phase boundary. Thus, for example, as the wave passes from ferrite

grain in direction $\langle 100 \rangle$ exhibiting $E_{\langle 100 \rangle} = 1.3 \times 10^5 \text{ MPa}$, into a grain in direction $\langle 111 \rangle$ indicating $E_{\langle 111 \rangle} = 2.9 \times 10^5 \text{ MPa}$, a strong deflection is to be expected as a result of change in its velocity. The effect of this deflection will be the elongation the ultrasonic wave path, the more the greater is the grain diameter. This shall explain the extension of the ultrasonic-wave passing time in coarse-grain material.

The analysis of pearlite grain structure permits a statement that the velocity of longitudinal ultrasonic wave shall depend on its orientation in relation to the direction of wave propagation. The value of the modulus E depends on the measurement direction.

In real conditions the incident ultrasonic wave meets the pearlite grain at various angles. Its path shall be changed due to deflection when the wave passes through mediums of different values of the modulus E . The wave path shall change more the larger interlamellar distance.

The presence of graphite in cast iron structure causes a considerable wave deflection at the graphite-matrix boundary, because the value of the modulus E for graphite ($E = 2.8 \times 10^3 \text{ MPa}$) is small compared to the value of this modulus for ferrite or pearlite.

The graphite shape is not unimportant if it appears that the energetic reflection coefficient at the graphite-matrix boundary is 0.6 in the 0 to 1 scale. Thus, as the wave passes from one of the graphite to the other, the resulting change in wave direction (dispersion), with consequential elongation of its path, may be quite considerable.

As a result of path elongation of the dispersed ultrasonic wave the time of its passage is longer and apparent velocity is reduced. The measurements assume that ultrasonic wave propagates in perpendicular line to the ultrasonic head application while its velocity is determined on the basis of a ratio of sample thickness, g , and the time of wave passage, t , ($c_L = g/t$). Thus, cast iron that differs by the matrix structure and graphite shape shall also differ by the velocity of ultrasonic wave. It appears that cast irons of similar mechanical properties, volume shares of structural constituents and graphite stereological parameters, shaped by the selection of chemical composition and solidification and by heat treatment, are not equivalent in ultrasonic respects [20]. In order to explain this phenomenon, the effects of heat treatment on structure and that of the structure on the propagation of ultrasonic waves must be analyzed.

In cast iron austenitizing process involves austenite saturation with carbon and the growth of austenite grains (Fig. 2) [22-26]. Eutectoid cementite and graphite are sources of carbon. Because of the lamellar structure of pearlite, the saturation of austenite with carbon from cementite decomposition takes place in a short time. If this source of carbon is missing or once depleted (for instance in cast iron with ferritic matrix) the process takes place as a result of dissolution of graphite precipitates. Dissolving precipitates change their shape and undergo degeneration (Fig. 3) There is also a possibility of partial loss of contact with the matrix [27] due to creation of voids resulting from dissolved graphite because of differences in the value of the coefficients of carbon diffusion and iron self-diffusion which are equal to $1.8 \cdot 10^{-7}$ and $7.3 \cdot 10^{-13} \text{ cm}^2/\text{s}$, respectively, at 1223 K.

In the austenitized cast iron, especially in oxidizing atmosphere, the graphite is degenerating and a network of oxides

is created with the time of holding at austenitizing temperature. The presence of magnesium oxides at graphite surface in spheroidal cast iron after ferritizing annealing was observed in the paper [28].

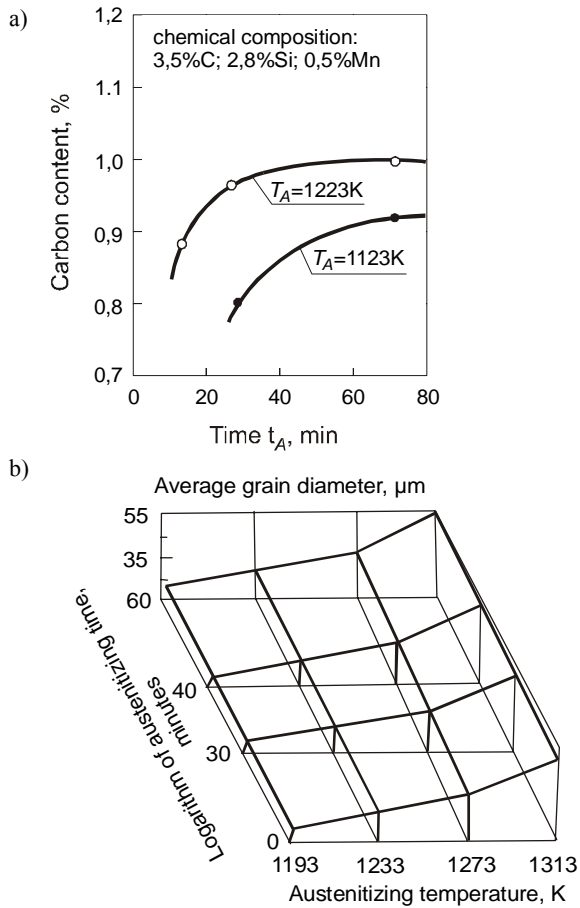


Fig. 2. a) Change in carbon content in the austenite of non-alloyed spheroidal cast iron depending on the austenitizing temperature, T_A , and austenitizing time, t_A ; b) Effect of austenitizing temperature and time on the average diameter of austenite grains

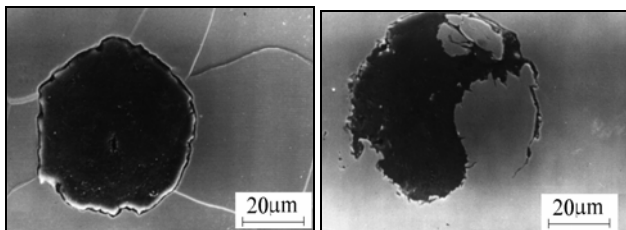


Fig. 3. Graphite degeneration with the time of austenitizing at temperature of 1173 K

In the light of this, the local lack of contact between the matrix and graphite, observed on heat-treated cast iron samples (Fig. 4), may be interpreted as void after oxides removed in

etching. It should be noted that gaps not always create a halo of uniform thickness.

A question comes to mind how to explain the possibility of gap creating and whether graphite dissolving is probable in conditions of lack of contact with the matrix. The ignition temperature of graphite isolated from iron ranges between 773 and 938 K, depending of heating rate. In the presence of oxygen from air it was found possible to saturate steel, which is in contact with isolated graphite, with carbon [29]. In case of cast iron, oxygen contained in the alloy or penetrating from surrounding atmosphere may participate in carbon combustion.

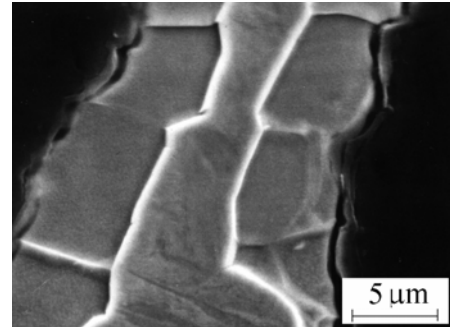


Fig. 4. Spheroidal cast iron austenitized at temperature 1173 K for 2 hrs and then cooled down in oil. Visible gaps between graphite and matrix

In the presence of oxygen, CO and CO_2 atmosphere may be created between the matrix and the graphite. A interrelationship, defined by the Boudour reaction ($2CO \leftrightarrow C + CO_2$), exists between carbon, carbon oxide and carbon dioxide. In the usually used austenitizing temperature (1173 K) the carbon oxide share in the gas phase exceeds 90%. It is assumed that adsorption of carbon atoms from CO and reaction of $2CO \leftrightarrow Fe_\gamma(C) + CO_2$ take place on the surface of matrix austenite boundary while carbon diffuses into austenite. As the content of carbon dioxide cannot exceed equilibrium value at a given austenitizing temperature the $CO_2 + C \rightarrow 2CO$ reaction takes place. The process continues until the moment of matrix saturation with carbon or graphite depletion. The diagram of such gap creation mechanism is illustrated in Fig. 5.

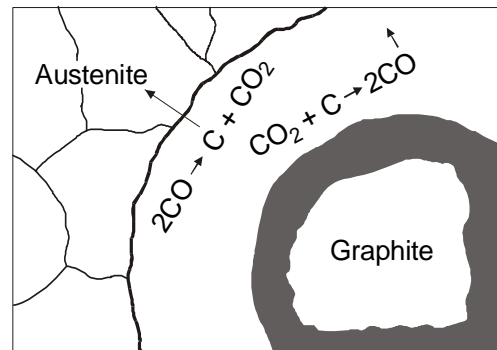


Fig. 5. The model of the process of carbon conveyance from graphite to austenite in conditions of gap existence

A course of gap creation process as a result of graphite precipitate concentration is also probable. The stresses at the graphite-matrix boundary may reach the order of 300 MPa just after solidification process completion. Once the casting has cooled down, the value of those stresses decreases to approx. 50 MPa. In the course of heat treatment aimed at transformation $A \rightarrow F + G$, the stresses at the graphite-matrix boundary may again rise to 300 MPa. On the other hand, if the $A \rightarrow P + G$ transformation is taking place during cooling, the value of those stresses shall be lower and equal to approx. 20 MPa. Once the casting is cooled down to ambient temperature the value of stresses shall drop to zero [30].

The stresses are caused mainly by different values of the linear coefficient of thermal expansion of graphite and matrix.

Graphite crystallizes in hexagonal arrangement, creating layers between which there are weak molecular bonds (4-10 kJ/mol). Strong covalent bonds exist between atoms in layers (420-500 kJ/mol). A consequence of such structure is the anisotropy of graphite properties (for instance the higher value the linear coefficient of thermal expansion and the higher value of the Young modulus in the direction of main hexagonal axis than that in the direction perpendicular to it) [31-33]. The main crystallographic axis of graphite layers forming a spherulite is consistent with the direction of precipitation radius (Fig. 6). Flake graphite precipitates also have a lamellar structure. If one takes into account that the value of linear coefficient of thermal expansion for Fe_γ is $18-19 \cdot 10^{-6} K^{-1}$ and the value of linear coefficient of thermal expansion of graphite in perpendicular direction to the base line at the temperature of 1473 K is $28-29 \cdot 10^{-6} K^{-1}$ [30], then, on account of the graphite porosity it may become concentrated during austenitizing. The consequence may be the appearance of gap between graphite and matrix at ambient temperature.

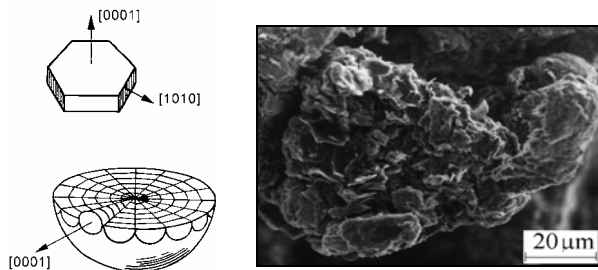


Fig. 6. Spheroidal graphite structure

The gap becomes 'healed up' in the ferritizing annealing when carbon diffusion takes place from the matrix towards graphite.

When the product of the frequency of longitudinal ultrasonic wave and the width of the gap between graphite and the matrix shall reach the value of $10^{-5} \text{ mm} \cdot \text{Hz}$, then a complete reflection of waves from matrix surface is to be expected. This will affect the elongation of the path, and thus the time of ultrasonic wave passage through the sample (Fig. 7).

An important parameter of alloy microstructure is the total length of the lines of microstructure component boundaries

related to unit surface. The speed of the longitudinal ultrasonic wave in cast iron with ferritic matrix rises with growing specific length of ferrite grain boundaries. In cast iron with pearlitic matrix it rises with growing specific length of cementite-ferrite phase boundaries. The value of the graphite-matrix boundary line is also significant, especially when it grows clearly as a result of graphite degeneration.

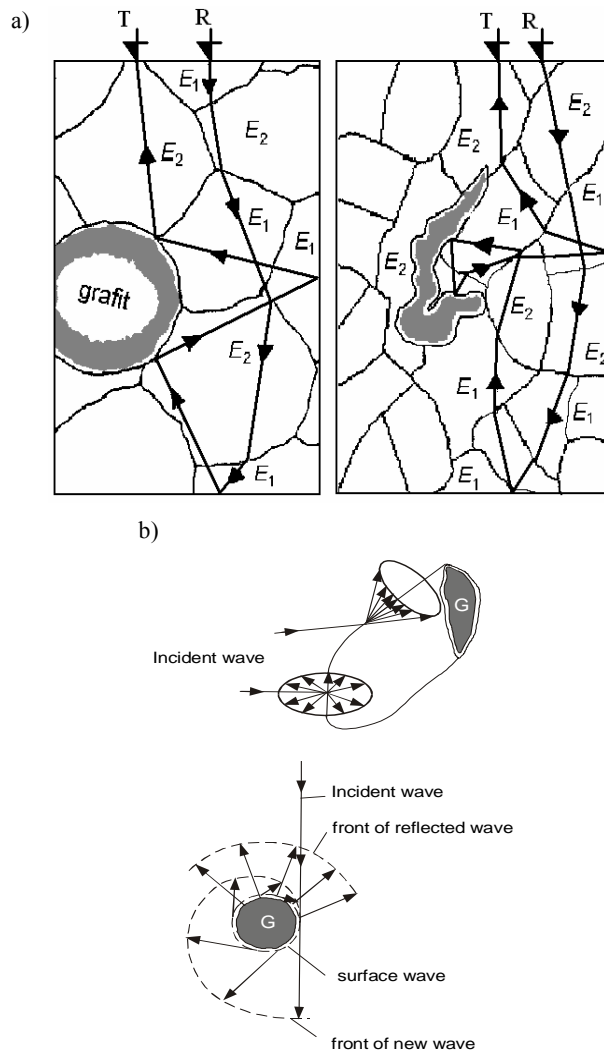


Fig. 7. (a) Schematic visualization of the path of the ultrasonic wave in heat treated cast iron, (b) Diffraction and dissipation of waves on flake and spheroidal graphite precipitates, T – transmitter, R - receiver

In this light it seems interesting to determine what has the stronger effect on the speed of the longitudinal ultrasonic wave – the stereological characteristics of graphite or the specific length of grain boundaries or the line of cementite-ferrite phase boundaries. The model material for the study of the relationship of the speed of ultrasonic wave on the specific length of the boundary line was cast iron with ferrite matrix and steel with

eutectoid content of carbon, as well as the ferritic and pearlitic spheroidal cast iron. It appeared that the change in the specific length of the boundary line in the cast iron with ferrite matrix by 10 mm/mm^2 shall cause a change in the speed of ultrasonic wave by approx. 30 m/s. In case of pearlite matrix the change in specific length of the line of cementite-ferrite phase boundaries by 10 mm/mm^2 shall cause a change in the speed of ultrasonic wave by approx. 0.75 m/s in steel with eutectoid content of carbon or by approx. 2 m/s in case of pearlitic spheroidal cast iron. In order to minimize the effect of the changes in the volume share and in the average number of graphite grains on the speed of ultrasonic wave, the tests were performed on samples of the same area of cast iron ingot. Different values of specific length of grain boundaries and cementite-ferrite line were obtained through change of austenitizing temperature.

The presented results show that in such complicated material as cast iron, changes in graphite morphology caused by heat treatment have much stronger effect on the speed of the longitudinal ultrasonic wave than the changes in matrix assessed by the specific length of the grain boundary lines or lines of cementite-ferrite phase boundaries. These changes do not yet have a visible effect on mechanical properties of cast iron, but already become an obstacle for the ultrasonic wave causing elongation of its path.

A more precise observation of the structure of cast iron, obtained in conditions of higher rate of cooling from liquid state or from the range of austenitizing temperature, indicates a presence of halos, of structure characteristic for lower cooling rates compared to matrix structure in areas more distant from graphite, around graphite precipitates. It may be explained as a result of the thermal effect of graphite, which exhibits more than two times higher value of the specific heat compared to the matrix material. Graphite has also a higher thermal conductivity [31-33].

During cooling graphite sheds the excess of heat to the surrounding layer of matrix, thus causing a slowdown of its cooling. The resulting thermal conditions are favorable for creating other structural constituents than in the remaining areas. For example, at a very high cast iron cooling speed from liquid state the halos of martensite, bainite and residual austenite are observed around graphite with transformed ledeburite observed in depth of the matrix [34] whereas in hardened cast iron ferrite precipitates appear around the graphite (Fig. 8). Such halos constitute a structural notch on which the ultrasonic wave becomes diffracted thus affecting the time of its passage through the material.

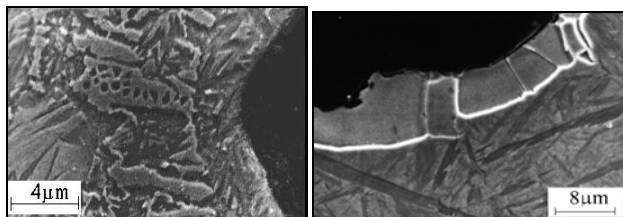


Fig. 8. The halos from phases formed around graphite precipitates that are characteristic for lower speed of cooling.

As a result of structure effect on the path and time of ultrasonic wave passage through the material the positions of its fronts are differentiated (Fig. 9) and there is an apparent speed variation.

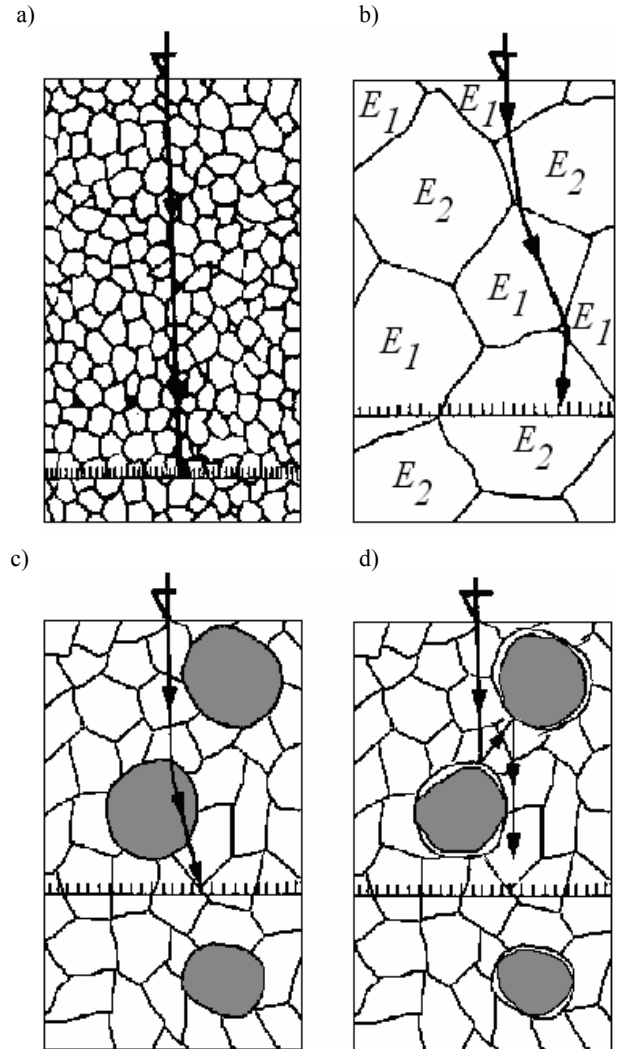


Fig. 9. Wave front displacement for the same time interval in steel and in cast iron, (a) steel with fine grain, (b) steel with large grain, (c) cast iron "as cast" condition, (d) cast iron – long time and high temperature austenitization

4. Conclusions

1. The effect of cast iron heat treatment is the creation of new obstacles in the path of propagating ultrasonic wave. As a result of reflections, the path of ultrasonic wave becomes extended and thus the wave travel time is longer. The consequence is an apparent reduction in this speed. Therefore, as-cast and heat treated iron of similar structure

and similar mechanical properties exhibit different values of ultrasonic wave speed.

- Application of ultrasonic wave for the inspection of mechanical properties of heat treated iron castings may be effective only in case of using consistent values of their heat treatment.

References

- Ziegler R., Gerstner R.: Die Schallgeschwindigkeit als kennzeichnende Größe für die Beurteilung von Gusseisen, *Giesserei H.* 3, 185-193 (1958)
- Bierwirth G.: Zörsörungsfreie Prüfung von Gusstücken durch Ultraschall, *Giesserei* 44, 477-485 (1957).
- Koppelman J., Frielinghaus R.: Die Bedeutung der Ultraschallmesstechnik für die Gefügebeurteilung von Eisenwerkstoffen, insbesondere Gusseisen. *Giesserei H.* 24, 802-809 (1966).
- W. Lenard: Badanie wytrzymałości na rozciąganie żeliwa szarego w odlewie – metodą ultradźwiękową. *Przegląd Odlewnictwa* Nr 2, 37-39 (1978).
- Orłowicz W., Gedeonova: Nedeštruktivna kontrola vlasnosti liatin ultrazvukom. Medzinárodná vedecká konferencia. k 35 výročiu založenia, Katedry metalurgie železa a zlievárenstva Hutnickej Fakulty TU Košice. 321-326 (1994).
- Pawłowski Z.: Bewertung der Gusseisenfestigkeit mittels Ultraschallmessungen. *Giessereitechnik H.* 3, 81-85 (1982).
- Yoshiaki Sano, Shigeki Moriyama: Evaluation of the quality of the gray iron casting material by ultrasonic testing. *Imono* Nr 6, 364-370 (1982)
- Hidehiko Kage, Yuichi Tanaka: Evaluation of cast iron quality by ultrasonic testing, *Imono* Nr 7, 408-414 (1984).
- Taku Ohide, Junih Mita, Katsuma Ikawa: Relationship between mechanical properties and ultrasonic velocity of cast iron. *Imono* Nr 2, 261-267 (1986).
- Jarvis J.: Ultrasonic in the foundry. *British Foundrymen.* August, 400-406 (1957).
- Vetiska A.: Zörsörungsfreie Ermittlung mechanischer kenngrößen an Gusstücken. *Giessereitechnik H* 9, 300-305 (1971).
- Yoshiaki Sano, Shigeki Moriyama: Evaluation of quality of the gray iron casting material by ultrasonic testing. *Imono* Nr 6, 364-370 (1982).
- Taku Ohide, Junih Mita, Katsuya Ikawa: Relationship between mechanical propertis and ultrasonic velocity of cast iron. *Imono* Nr 2, 261-267 (1986).
- Zbinden H.: Der Ultraschall als Mittel der Werkstofforschung. Sonderdruck aus *Technica* 14 und 17 durch Krautkrämer, 3-17 (1969).
- Henderson H.: Ultrasonic velocity technique for quality assurance. *Foundry Trade Journal*, February 21, 203-206 (1974).
- Pris J.: Gefügeuntersuchungen an Gusswerkstoffen mit Hilfe von Ultraschall. *Giessereitechnik H* 8, 267-274 (1974).
- Ors J.: Gray cast iron test pices under mechanical stresses. Preprints VII IC Ndt. Warszawa Nr J-01 (1973).
- Kovacs B.: Bestimmung einiger mechanischer und physikalischer Eigenschaften von bainitischen Gusseisen mit Kugelgraphit mittels Resonanzfrequenz. *Giesserei Praxis* Nr 15/16, 279-285 (1995).
- Ahmet Topuz, Emine Topcu, Adem Bakkağlu.: Microstructural investigation of austempered ductile irons with ultrasonic method. *Praktische Metallographie.* Nr 6, 278-287 (1997).
- Orłowicz W.: Ocena właściwości mechanicznych żeliwa sferoidalnego metodą ultradźwiękową. *Zeszyty Naukowe Politechniki Rzeszowskiej* nr 66, *Mechanika* z. 20 Rzeszów 1990.
- Obraz J.: Ultrasonic in measuring technique. *Techcal Scientific Publication*, Warsaw (1983).
- Röhrig K., Farihurst W.: Wärmebehandlung von Gusseisen mit Kugelgraphit. *Giesserei - Verlag GmbH.* Düsseldorf 1979.
- Shea M., Rynitz E.: Zwischenstufenvergüteten Gusseisen mit Kugelgraphit auf optimale Zähigkeit. *Giesserei – Praxis* H 19, 280-286 (1987).
- Henke E.: Wärmebehandlung von Gusseisen. *Giesserei – Praxis* Nr 23-24, 351-384 (1976).
- Dorazil E.: Effect of austenitizing temperature on isothermal decomposition of austenite in non-alloyed gray cast iron. *Levarenstvi* Nr 12, (1970).
- Jonuleit A.: Austenitkorngrossendiagram und einige Aspekte des Austenitkornwachstums für unlegiertes Gusseisen mit Kugelgraphit. *Giessereitechnik* Nr 6, 163-170 (1977).
- Bunin K., Jacenko A.: Roztvorienije grafita w magniewomczugunie pri nagriewie. *Mietałlowiedienije i Termiczeskaja Obrabotka* Nr 5, 34-37 (1961).
- Haensel G., Mitsche R., Dichtl.: Neue Untersuchungen über die Herstellung und Überwachung der Qualität von Gusseisen mit Kugelgraphit, 40MKO, Moskwa ref. 15 (1973).
- Pachowski M.: O mechanizmie przenoszenia węgla z grafitu do osnowy metalowej żeliwa sferoidalnego. *Zeszyty Naukowe Politechniki Rzeszowskiej* Nr 25. *Mechanika* z. 8, 15-23 (1985).
- Jepanczincew O.: K rasczetu napraženij w sierom czugunie na granice rozdziela grafitnoje wkluczenije – matrica. *Litiejnoje Proizvodstwo* Nr 12, 6-9 (1975).
- Girszowicz N.: Krystalizacja i swojstwa czuguna w otlivkach. *Maszynostrojenije*, Moskwa, Leningrad 1966.
- Podrzucki Cz.: Żeliwo. Struktura, właściwości, zastosowanie. *Wyd. ZG. STOP.* Kraków 1991.
- Encyklopedia Techniki. *Metalurgia.* Wyd. Śląsk. Katowice 1978.
- Trytek A.: Właściwości eksploatacyjne uszlachetnionych powierzchniowo części maszyn z żeliwa sferoidalnego. *Praca doktorska, Politechnika Rzeszowska, Rzeszów* 2001.