Journal of Materials Science and Engineering A 11 (10-12) (2021) 120-128
doi: 10.17265/2161-6213/2021.10-12.003

Determining the Thermal Conductivity in Walls of Cast Iron Castings by the Ultrasound Technique

Jerzy Stanisław Zych[1], Marcin Myszka[1] and Krzysztof Piotrowski[2]

1. Faculty of Foundry Engineering, AGH University of Science and Technology, Reymonta 23, Cracow 30-059, Poland

2. Krakodlew S.A., Ujastek 1, 30-969 Cracow, Poland

Abstract: Research results concerning the application of ultrasound technique for determining the averaged thermal conductivity in walls of castings produced of cast iron (solidifying in a steady system) containing carbon precipitates in a graphite form, are presented in the hereby paper. Investigations concern castings of unalloyed cast iron. The influence of the form of graphite precipitates on the cast iron thermal conductivity as well as on the propagation velocity of the ultrasound wave, including the longitudinal wave velocity C_L, was investigated in the study. The influence of the graphite form, described by the shape indicator (f), on the thermal conductivity (λ) (determined on samples by the steady heat flow method) as well as the influence of this indicator (f) on the wave propagation velocity (C_L), was investigated. A series of melts of cast iron, of the near eutectic chemical composition, were performed. Magnesium introduced in a wide range, allowed obtaining various graphite forms from flake, via mixed, vermicular to nodular. Dependences: λ = f(C_L), C_L =f(f) were determined and at the final phase the empirical dependence λ = f(C_L) was also determined. The thermal conductivity and ultrasound wave velocity were tested on the same samples. The thermal conductivity coefficient of cast iron (λ) was changing in a wide range from approximately 32 to 46 W/s·m, while the wave velocity C_L respectively: from approximately 4,300 to 5,800 m/s. The empirical dependence λ = f(C_L), determined in the described variability ranges, is of a linear character and the correlation level equals: $R^2 = 0.87$. The validation of the experimental results was performed on cast iron castings of slag ladles, since they are required to be of a good thermal conductivity. The possibility of assessing the thermal conductivity directly in walls of such castings by means of non-destructive ultrasound method, was confirmed. The real thermal conductivity determined in the walls of the castings is used to simulate the heating and cooling process of slag ladles, ingot molds and similar structures, which was one of the main objectives of the research.

Key words: Thermal conductivity, ultrasounds, cast iron, research tools.

1. Introduction

The thermal conductivity of construction materials is, in several cases, the most important physical property, deciding on their suitability. Cast iron is one of the most widely used materials, which are often required to be characterized by a good thermal conductivity. In situations when structures and elements are subjected to thermal shocks, materials of an increased ability to carry away heat and having a higher thermal conductivity are required. The thermal conductivity is the basic feature deciding on these structures' durability and service life.

There are a lot of examples of such structures in modern machines and devices. They can be found in every technical field. In automotive such examples constitute elements of internal combustion engines (heads, cylinders, housings, exhaust manifolds, brake plate disks, pistons, etc.), while in the power industry: power unit bodies, turbine rotors, elements of combustion boilers, slag ladles. In metallurgy: ingot moulds, ingot moulds bottom plates, rollers, drop forging dies, while in foundry practice: metal moulds, moulds for gravity die castings. A majority of these structures and parts of machines and devices are produced by means of casting of various kinds and

Corresponding author: Jerzy Stanisław Zych, PhD, professor, research fields: material engineering, metallurgy, foundry engineering, ultrasonic testing.

grades of foundry alloys. Previously as well as currently, ferrous alloys (mainly cast iron) and cast steels (to a slightly lower scale) dominate among materials applied for operations under the mentioned conditions.

Operational conditions, temperature change ranges in individual thermal cycles, to which the above mentioned structures are subjected, as well as their service life (working time, number of thermal cycles) are different and specific for each structure. However, in their thermal fatigue processes a certain group of characteristic and similar effects occur, which finally leads to material continuity interruptions. The most often these elements are subjected to quite violent (often unilateral) heating followed by slow cooling. Such heating way forces high temperature gradients on cross-sections of walls and leads to thermal stresses. The level of these stresses depends on temperature gradients and elastic properties of materials. However, stresses occur always.

Gray cast iron (unalloyed) is the material, in which a form and amount of graphite precipitates decides on their thermal conductivity. The matrix type, from ferritic, via ferritic-pearlitic to pearlitic is influencing to much lower degree. Gray cast iron with flake graphite has the highest thermal conductivity, while with nodular graphite the lowest. In between these extreme forms of graphite precipitates there are gray cast irons with mixed forms (the so-called Vari Morph cast irons) [1-6] or vermicular cast iron.

Cast iron is the foundry alloy characterized by a high sensitivity for cooling rates. Metallographic structure, including amount, size and—to a certain degree—graphite shape depend on a cooling rate. This, in turn, depends on casting walls thickness, its shape, heat exchange conditions, material out of which a mould was made, etc. Thus, in order to assess the thermal conductivity of the given element or structure a series of samples should be taken (by means of trephination) from the casting and the thermal conductivity of each sample should be measured separately. It is not always possible.

The aim of the described investigations is the development of non-destructive method of determining the thermal conductivity directly in walls of castings made of cast iron. Our own investigations [6-8] as well as several other works [9-11] indicate physical bases for using the ultrasound technique. The longitudinal wave velocity in cast iron as well as its thermal conductivity depends mainly on forms and amounts of graphite precipitates [7-9, 11-18]. Thus, it should be expected that between these two physical properties: thermal conductivity and ability of ultrasound wave propagation, the velocity of which is its indicator, there is a well correlated dependence: $\lambda = f(C_L)$.

Determination of such dependence will allow assessing the real suitability of structures made of cast iron for operations under conditions of thermal shocks. In addition, it could be used as a controlling element of castings intended for operations under conditions of thermal shocks and heat fatigue.

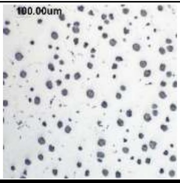
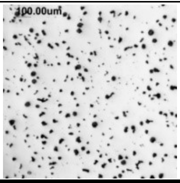
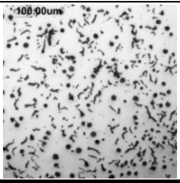
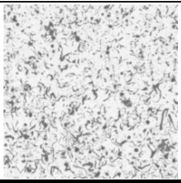
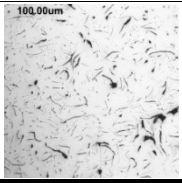
2. Own Investigations

2.1 Aim and Methodology of Investigations

The aim of our research was the determination of the empirical dependence between the thermal conductivity coefficient (λ) and the ultrasound wave velocity (C_L) in cast iron. Samples, made of near-eutectic cast iron of the following chemical composition: C = 3.3%-3.6%, Si = 2.6%-2.95%, Mn < 0.1%, P < 0.02%, S < 0.01%, Mg = 0.005%-0.035%, were used in this research. Initial cast irons were subjected to secondary metallurgy—spheroidisation by the controlled introduction of various amounts of magnesium. Obtaining a wide spectrum of graphite precipitate forms in samples from individual melts was strived for. Each time test coupon, Y2 type, was cast from the prepared cast iron, in accordance to the binding standard.

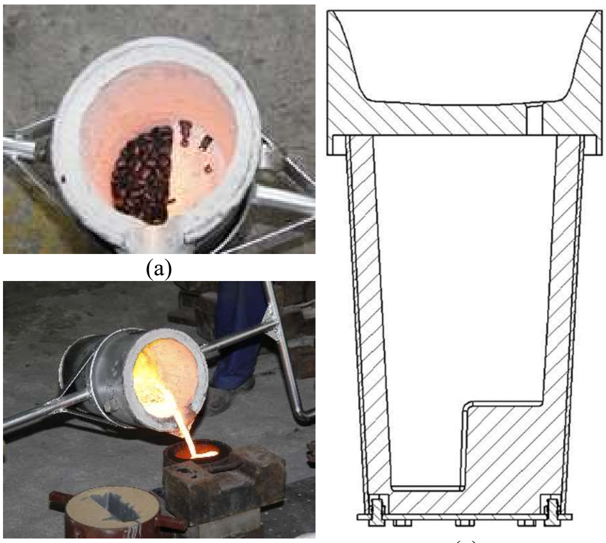
The obtained cast iron was of the ferritic matrix, which contained various forms of graphite (Table 1), in dependence of the introduced amount of magnesium (flake graphite, vermicular, modular and also their mixtures in various proportions).

Table 1 Examples of microstructures of the obtained cast iron.

Graphite shape indicator *f*	0.78	0.7	0.62	0.59	0.49	0.31
Micro-structure (magnification 100×)						

(a) (b)

Fig. 1 Research stand for spheroidisation performed by means of the elastic conductor method. (a) Project; (b) Set up after introducing the elastic conductor.



(b) (c)

Fig. 2 Slender ladle with the Tundish cover. (a) Ladle filled with the matrix; (b) Pouring from the ladle; (c) Ladle cross-section.

Samples for tests were taken from test coupons. Melts were performed in the experimental casting house in the Faculty of Foundry Engineering AGH. The spheroidisation process was carried out by two methods: elastic rod method and Tundish technology (ladle with a cover). Research stands developed and built in the Faculty of Foundry Engineering are presented in Figs. 1 and 2. The possibility of precise dosing spheroidising matrices exists in both solutions and this allowed producing cast irons with controlled (planned) forms of graphite precipitates. Test coupons of Y2 type were cast from the produced cast iron. Samples for structure testing, thermal conductivity and ultrasound investigations were made from Y2 test coupons.

2.2 Own Investigations

Own investigations of cast irons contained three fields:

- Metallography with assessments of the graphite shape indicator (*f*),
- Determinations of the thermal conductivity (λ),
- Determinations of the ultrasound wave velocity (C_L).

The same investigation ranges were performed for cast irons obtained in successive melts. The purpose of tests designed in such a way was the determination of the empirical dependences between the graphite shape indicator and the thermal conductivity and longitudinal wave propagation velocity.

2.2.1 Assessment of the Graphite Shape Indicator "*f*"

Microscopic images were subjected to stereological analysis utilizing software ImageJ. The following data were each time determined:

- number of graphite precipitates on mm^2 (with omitting precipitates being on the image edges and the ones of surfaces smaller than 0.0785 μm),

- percentage fraction of the graphite surface,
- surface of each precipitate,
- diameter of the circle described on the precipitate, with the diameter corresponding to the greatest linear dimension of the separation.

Graphite shape indicator f was determined for each precipitate according to Ref. [13], by means of Eq. (1):

$$f = \frac{A_v}{A_C} \tag{1}$$

where:

A_v—surface of graphite precipitate (mm^2),

A_c—area of a circle, whose diameter is equal to the particle of the highest dimension (mm^2).

It was assumed that the graphite shape indicator is changing within the following boundaries:

0.00-0.34 for flake graphite,

0.35-0.64 for vermicular graphite,

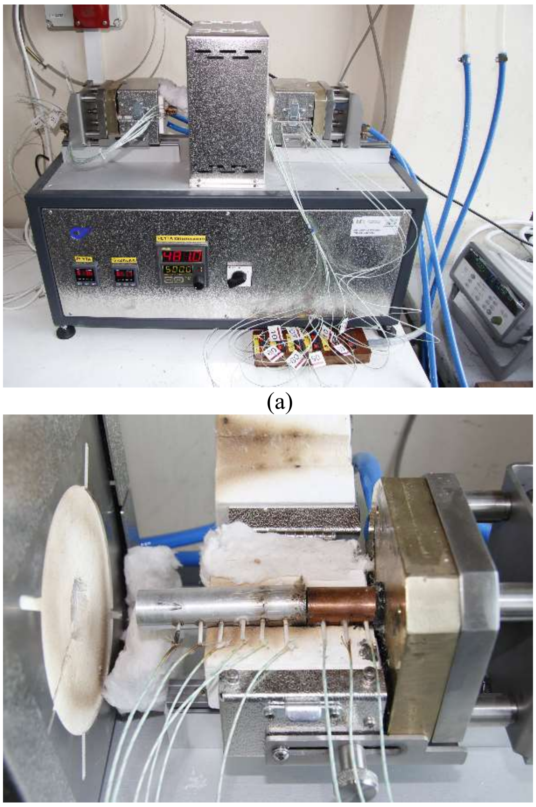
0.65-1.00 for modular graphite.

Numbers of precipitates of the shape indicator f falling within individual ranges were successively summed up and their percentage fraction—in relation to all graphite precipitates—was determined. The separate, average indicator f was determined for each range. This indicator constituted the base for calculating the main shape indicator f based on weighted mean [1, 2, 13].

2.2.2 Measurement of the Thermal Conductivity

The thermal conductivity was determined under conditions of a steady heat flow. Measurements were carried out on the authors' research setup, which was designed and constructed in the Faculty of Foundry Engineering AGH (Fig. 3).

There are several solutions within methods of testing thermophysical properties of materials, however no one is universal or the best. The authors applied the testing method under conditions of a steady heat flow (stable heat flux passing through the selected material layer).



(a)

(b)

Fig. 3 Research setup for testing the thermal conductivity. (a) General view; (b) Placement of the sample together with the copper standard.

In this solution the sample is heated by the heating element and the unidirectional heat flux is forced. For determining the thermal conductivity coefficient (λ) one of the basic equations concerning the thermal conductivity was used. Eq. (2) describes the dependence between the intensity of the heat flux (q), passing through the sample of length "l", related to the unit area by the temperature gradient: T_2 - T_1 and conductivity coefficient.

$$\mathrm{a}_v = \frac{\lambda_X(T_2 - T_1)}{l_x} = \frac{\lambda_w * (T_4 - T_3)}{l_w} \tag{2}$$

In our authors' solution the method of conductivity measuring using two samples, the tested one and the reference sample placed in series, was applied (Fig. 1b). The thermal conductivity coefficient was determined from Eq. (3).

$$\lambda_x = \lambda_w * \frac{l_x}{l_w} * \frac{(T_4 - T_3)}{(T_2 - T_1)} \tag{3}$$

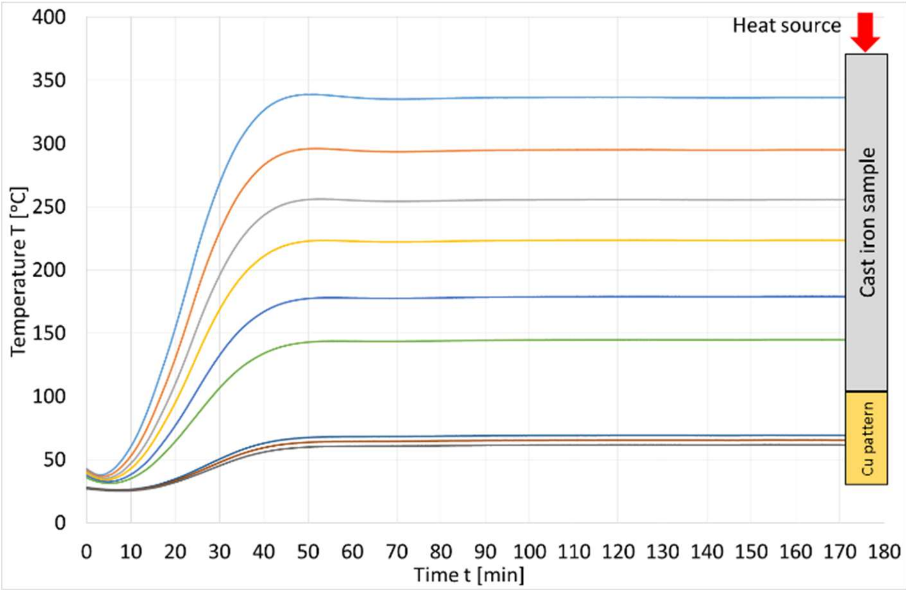


Fig. 4 Example of the temperature stabilizing process in measurement points during the thermal conductivity tests.

During the test the sample is heated from one side up to the state when the temperature in all measuring points, in which thermocouple elements of K type are placed, will be stable (Fig. 4). At the opposite side of the heater there is the copper standard, in which thermocouples are also placed. At the end of the measuring line there is a brass cooler with a forced internal water flow. The Keysight device was used for data recording. After finishing the measurement and performing appropriate calculations in the Excel software, the value of the thermal conductivity coefficient (λ) was obtained.

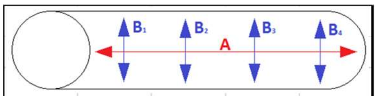
2.2.3 Measurement of the Ultrasound Wave Velocity

Ultrasound measurements were performed on the same samples. Ultrasound tester CT-3 (Fig. 5) was applied for measurements. This tester measures time of the ultrasound wave passage between the sending and receiving heads. When the length of the tested sample is known, it is possible to calculate the ultrasound wave velocity.

The obtained result, in case of the thermal conductivity measurements as well as in case of ultrasound tests, is the value averaging along the sample length. It is very similar under real conditions of the casting wall since the whole cross-section of the tested structure influences the real conductivity. It is clearly shown by the example presented in Table 2. Measurements performed in the sample cross-section are different, however their average value is very

Fig. 5 Ultrasound tester CT-3 prepared for tests.

Table 2 Example of the ultrasound measurement.



	V [m/s]			
A	5603			
B_i	5592	5605	5613	5606
$B_{śr}$	5604			

similar to the measurement performed along the tested roller. In consideration of this fact, the authors recognised ultrasound tests as the best suitable for forecasting other material properties of castings, e.g. their thermal conductivity.

2.3 Investigation Results

Along with an increase of the nodular graphite fraction (which means that coefficient *f* value is increased) the ultrasound wave velocity increases, while the thermal conductivity value decreases (Fig. 6).

The results presented as a dependence of the thermal conductivity and ultrasound wave velocity: λ = f(C_L) are shown in Fig. 7. This allowed determining the trend line and the equation describing this line. Within the described variability ranges of the wave velocity and thermal conductivity, characteristic for cast iron with graphite in ferritic matrix, dependence: λ = f(C_L) is linear (Eq. (4)).

$$\lambda = -0.0078 \cdot C_L + 79{,}526 \left[\frac{W}{m \cdot s}\right] \qquad (4)$$

This dependence is relatively well correlated (R^2 = 0.874). Relatively small deviations constitute bases for stating that there is a real possibility of predicting such property as the cast iron thermal conductivity on the basis of direct ultrasound measurements performed on the finished casting. Investigations are still continued in order to increase the number of samples and to determine explicitly empirical dependences.

2.4 Results of Industrial Tests

A slag ladle, often produced of vermicular cast iron, belongs to the group of castings used in the metallurgical industry. Ultrasound tests were performed on the casting shown in Fig. 8. The results are presented in Table 3. Values of the thermal conductivity in selected places of the slag ladle were calculated on the bases of measurements of the wave velocity in the casting and on the previously determined dependence: λ = f(C_L) (Eq. (4) and Fig. 7). Determined values are the average values for walls in the given place of the ladle.

This results from the fact that the wave velocity on the wall cross-section is of the average value, which is a consequence of the applied methodology of ultrasound measurements. The wave velocity (C_L ~5,300 m/s) indicates that this ladle is produced of vermicular cast iron. The thermal conductivity calculated on the basis of wave velocity measurements (Eq. (4)) also corresponds to the structure of vermicular cast iron.

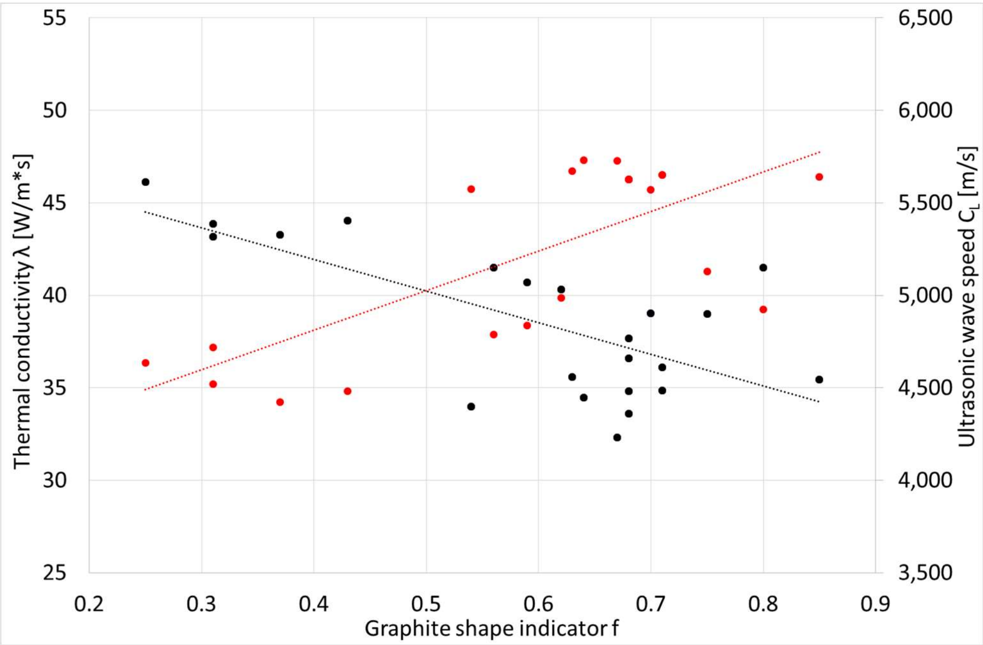


Fig. 6 Dependence of the thermal conductivity (black) and ultrasound wave velocity (red) on the graphite shape indicator value.

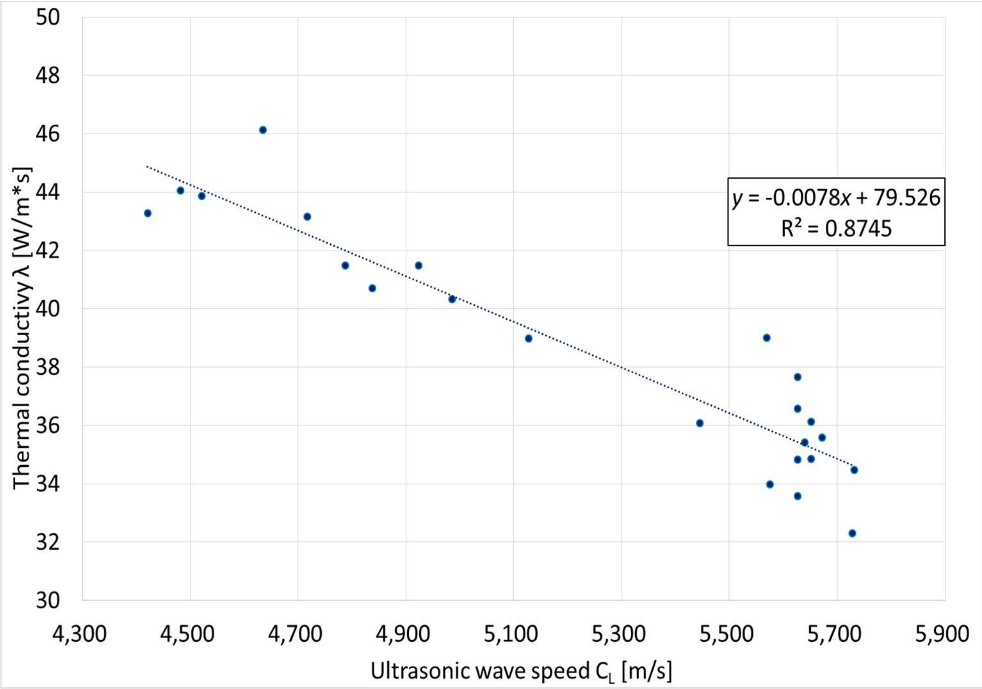


Fig. 7 Dependence of the cast iron thermal conductivity coefficient and ultrasound wave velocity.

Table 3 Results of industrial tests.

No.	Place of measurement	Measuring thickness (mm)	Transition time (µs)	Wave speed (m/s)	Thermal conductivity (W/m·K)
1	Handle-top	70.0	13.3	5,469	36.87
2	Handle-top	69.0	13.1	5,476	36.81
3	Handle-bottom	123.0	23.5	5,348	37.81
4	Collar	100.5	20.5	5,432	37.16
5	Collar	100.1	20.55	5,396	37.44

Fig. 8 Slag ladle of volume $V = 15$ m^3, produced of cast iron of a mixed graphite form, including vermicular.

In a similar way as with the slag ladle it is possible to measure the thermal conductivity in walls of each casting produced of cast iron containing graphite in its structure.

3. Conclusions

Analyses of the obtained results allowed drawing the written below conclusions.

- Two physical properties of cast irons containing graphite in their structure:

(1) thermal conductivity (λ),

(2) ability to propagation the ultrasound wave, measured byits velocity (C_L),

depend, first of all on the graphite form, and much weaker on the matrix.

- Graphite form described by its shape indicator is the parameter of the cast iron structure, which decides—to a similar degree—on the thermal conductivity and on the propagation of the ultrasound wave. This provides the basis of looking for the empirical dependence between the wave velocity and thermal conductivity of cast iron.
- The empirical dependence between the ultrasound wave velocity and thermal conductivity of cast iron, containing graphite of various forms, is of a linear character. This concerns the ranges of wave velocity changes, in such cast irons, from app. 3,900 to 5,800 m/s.
- Ultrasound, non-destructive, method of determining the thermal conductivity of cast iron containing graphite of various forms in casting walls is especially important for elements and structures, which are subjected to thermal shocks.
- Direct measurements performed on castings are "attractive", due to the simplicity of research methodology and because they provide the real image of the thermal conductivity in the whole casting, which is especially important in high-dimensional castings.
- Ultrasound measurement of conductivity is also "attractive" due to a short time of its performing in comparison with other methods of conductivity tests.
- In addition, an ultrasound measurement can be applied to determine the coefficient of heat penetration through a flat wall of cast iron casting.

Funding

This research was performed within realization of Project: POIR. 01.01.01-00-0965/17.

References

[1] Zych, J., and Postuła, J. 2018. "Cast iron 'Vari-Morph' (VM) with Graphite of Several Forms—Material for Castings of Special Destinations." In *Proceedings of the 73rd World Foundry Congress "Creative Foundry"*, 23-27 September 2018, Krakow, Poland, pp. 149-50.

[2] Zych, J., Myszka, M., and Kaźnica, N. 2019. "Control of Selected Properties of 'Vari-Morph' (VM) Cast Iron by Means of the Graphite Form Influence, Described by the Mean Shape Indicator." *Archives of Foundry Engineering* 19 (3): 43-8.

[3] Jura, S., and Jura, Z. 2001. "Influence of Chemical Constitution and Graphite Spheroidization Grade on Mechanical Properties of Cast Iron." *Archives of Foundry Engineering* 1 (2): 167-74.

[4] Jura, S., and Jura Z. 2001. "Influence of Stereological Functional Parameters of Graphite on Ductile Cast Iron's Mechanical Properties." *Archives of Foundry Engineering* 1 (2): 175-85.

[5] Stawarz, M., and Jura, S. 2002. "Stereological Parameters of Graphite and Chemical Constitution Determining Ductile Cast Iron's Mechanical Properties." *Archives of Foundry Engineering* 2 (4): 446-53.

[6] Postuła, J. 2017. "Production of Cast Iron with Variable Graphite Morphology. Evaluation of Solidification Process, Study of Microstructure and Selected Physical, Mechanical and Utility Properties." M.Sc. thesis, Department of Foundry, AGH Cracow-Poland.

[7] Zych, J., Myszka, M., and Snopkiewicz, T. 2019. "Thermal Conductivity of 'Vari-Morph' (VM) Cast Iron with Graphit of Several Forms." In *Proceedings of the International Conference of Metals, Ceramics and Composites*, 25-27 September 2019, Warna, Bulgaria, pp. 27-8.

[8] Zych, J. 2015. *The Role of Graphite Morphology in Forming of Thermal Fatigue Resistance of Cast Iron*. Inżynieria Materiałowa-Material Engineering. No. 5, pp. 343-7. ISSN 0208-6247.

[9] Orłowicz, A. 2000. *Applied Ultrasound in Foundry.* Katowice: PAN.

[10] Krautkramer, J., and Krautkramer, H. 1983. *Ultrasonic Testing of Materials*. New York: Springer Verlag.

[11] Zych, J. *Cast Iron Thermal Fatigue Resistance—Influence of Graphite Shape*. Seria Mechanika-Mechanic Series, pp. 51-64. ISSN 0860-097X.

[12] Zych, J., and Falęcki, Z. 1997. "Determination of the Mechanical Properties of Gray Cast Iron Using the Ultrasonic Method." Zeszyty Naukowe AGH, No. 4. Kraków. (in Polish).

[13] Patiero, V., Tosto, S., and Natale, E. 1997. "Microstructural Characterization and Mechanical Properties of Various Grade of Nodularity in S. G. Iron." 44 I. F. C., Paper No. 4, Florence.

[14] Walton, C. F., and Opar, T. J. 1981. "Covering Data on Gray, Malleable, Ductile, White, Alloy and Compacted Graphite Irons." In *Iron Castings Handbook.*

[15] Zych, J., and Jędrzejczyk, D. 1991. "Tests of Resistance to Thermal Fatigue of Cast Iron with Vermicular Graphite." *Przegląd Odlewnictwa* 6: 215-8. (in Polish)

[16] Wróbel, J. 2013. "Thermal Fatigue Resistance of ADI Cast Iron." PhD thesis, Faculty of Foundry Engineering AGH.

(in Polish)
[17] Żyrek, A. 2014. “Production of Vermicular Cast Iron by the Inmold Method with the Use of Magnesium Master Alloys and Evaluation of Its Resistance to Thermal Fatigue.” PhD thesis, Faculty of Foundry Engineering AGH. (in Polish)
[18] Podrzucki, C. 1991. *Żeliwo. Struktura, właściwości, zastosowanie* (Vol. 1 and 2). Kraków: Publishing house: ZG STOP. (in Polish)