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THERMAL CONDUCTIVITY OF MOULDING SAND WITH CHEMICAL BINDERS, ATTEMPTS OF ITS INCREASING

PRZEWODNOŚĆ CIEPLNA MAS FORMIERSKICH ZE SPOIWAMI CHEMICZNYMI, PRÓBY JEJ ZWIĘKSZENIA

The investigation results of the thermal conductivity of the selected group of moulding sands with chemical binders, mainly organic, are presented in the hereby paper. Studies encompassed also moulding sands into which additions improving the thermal conductivity were introduced. Two testing methods were applied, i.e. investigations at a steady and unsteady temperature zone. For investigations at a steady temperature zone the new original experimental stand was designed and built, adapted also for testing moulding sands with binders undergoing destruction at relatively low temperatures.

Keywords: thermal conductivity, moulding sands, investigation methods, binders

W pracy przedstawiono wyniki badań zdolności do przewodzenia ciepła wybranej grupy mas ze spoiwami, głównie organicznymi. Badaniami objęto również masy, do których wprowadzono dodatki dla zwiększenia przewodności cieplnej. Zastosowano dwie metody badań przewodności cieplnej, tj. badania w ustalonym polu temperatury i badania w nieustalonym polu. Dla badań w stacjonarnym polu zbudowano nowe, oryginalne stanowisko pomiarowe, dostosowane do badań mas ze spoiwami ulegającymi destrukcji w stosunkowo niskiej temperaturze (spoiwa organiczne). Wyniki badań przedstawiono graficznie w układzie: λ = f(T) – współczynnik przewodzenia w funkcji temperatury. Wykazano istnienie minimum funkcji w temperaturze niższej niż w przypadku mas klasycznych. Wprowadzanie do masy dodatku grafitu zwiększa jej przewodność. Wprowadzenie grafitu nie wpływa istotnie na proces wiązania mas furanowych. Masy ze szkłem wodnym charakteryzują się lepsza przewodnością, szczególnie w wyższych (T >400°C) temperaturach.

1. Introduction

The intensity of heat exchanging between metal and a sand foundry mould is one of the factors deciding on the metallographic structure of castings. A majority of foundry alloys is sensitive to the cooling rate, which means that their structure depends on the kinetics of the heat transfer to the mould. A heat flow from a casting to sand mould is of unsteady character, time variable. As it is generally known, in all transient processes enthalpy changes occur both in the agent giving up the heat – in this case: metal and in the agent taking the heat – in this case: moulding sand. A heat flux flowing from metal to the mould depends on the temperature gradient on the contact surface of metal and the mould and on the processes of propagation and accumulation of heat in the mould, which in turn depends on thermophysical properties of the mould material. These properties are determined by values related to the material and mould state, which are mutually interrelated. To the group of these properties belong

$$b_2 = \sqrt{(\lambda_2 \cdot c_2 \cdot \rho_2)}\alpha_2 = \frac{\lambda_2}{c_2 \cdot \rho_2} \tag{1}$$

$$b_2 = \sqrt{(\lambda_2 \cdot c_2 \cdot \rho_2)} \tag{2}$$

where:

α_2 – coefficient of temperature conduction, [m^2/s]
b_2 – coefficient of heat accumulation, [(W·$s^{1/2}$)/(m^2· K)]
ρ_2 – specific gravity, [kg/m^3]
λ_2 – thermal conductivity, [W/(m K)]
c_2 – specific heat, [J/(kg K)]

It is known, from the general theory of heat exchanging in transient processes, that between the mentioned physical values, connections of a determined physical sense exist and that they are in a form of equations (1) and (2):

Since the moulding sand is not a homogeneous body, all mentioned above coefficients determining thermophysical properties are of a substitutive character. They concern the moulding sand – of the determined composition prepared under the given conditions – out of which the mould of the given compaction was made. In addition, they concern the mould which was poured by the selected alloy (of the determined temperature) either in its wet state or after drying [2]. The anisotropy of the moulding sand compaction, which depends on the compacting direction, can also influence these coefficients values. Due to the above, the coefficients values – determined by any method – can only serve for relative comparisons of various moulding sands. Thus, the application of the obtained results for thermal calculations of the given sand moulds must be done with a lot of caution, since large

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divergences can occur [1, 2]. The majority of investigations carried out up-to-date concerned assessments of thermophysical properties of moulding sands with bentonite. However, in the foundry practice more and more often moulding sands with chemical binders, organic and inorganic, are used. Organic binders are substances based on carbon compounds, which undergo the pyrolisis at being heated after the mould pouring with liquid metal. The heat of the pyrolysis changes the kinetics of the mould heating and casting cooling. At the current state of knowledge, this problem is poorly investigated and described. It is even considered, that the thermal conductivity determination of moulding sands with chemical binders is not possible, due to the pyrolysis of binders [2].

Descriptions of increasing the heat transfer ability of moulding sands can be found in references as well as tests of doing this in the foundry practice occur. It can be achieved by changing the moulding sand matrix (e.g. from quartz into chromite) or by introducing certain additions (materials) increasing the thermal conductivity (e.g. graphite, cast steel shot, etc.).

The series of investigations on the assessment of thermophysical properties of moulding sands with chemical binders as well as sands with additions improving their thermal conductivity were performed within the hereby study. These own investigations were preceded by the development of the new testing method of the moulding sands conductivity and by building of the new experimental stand.

2. Own investigations

2.1. Object of investigations and their range

The object of investigations constituted moulding sands with organic binder (furan resin) and the quartz matrix and with additions improving the sand thermal conductivity (graphite and cast steel shot). An increase of the mould ability for a fast heat transfer can be realised by the given below operations.

- Changing of the moulding sand compaction degree.
- Replacing the quartz matrix by another matrix of a higher ability of taking and transporting heat from the surface of the casting being cooled into the mould depth and outside it.
- Introducing additions significantly improving the thermal conductivity.
- Introducing into the moulding sand additions increasing its heat accumulation ability and thus, improving general conditions of a heat transfer from the casting being cooled.
- Application of traditional external chills.
- Making the mould from another material (e.g. applying a metal mould or core).

The performed investigations concerned the determination of thermophysical coefficients of moulding sands with furan binder, in a wide range of temperatures.

- Determination of thermophysical properties of the reclaim based moulding sand, for two compaction levels.
- Determination of thermophysical properties of the moulding sand with the chromite and magnesite matrices and comparing them with the moulding sand with the quartz matrix.
- Determination of properties of moulding sands with the graphite addition (at two levels), as the component which can improve the moulding sand ability for the heat transfer.
- Determination of the thermal conductivity of the moulding sand with additions of cast steel shots, increasing the ability to accumulate heat.

Investigations of thermophysical properties were supplemented by the DTA and DTG tests of moulding sands with furan resin with the use of the derivatograph. Their aim was to determine the temperature range, at which the decomposition process and organic binders pyrolysis occurred and to confirm thermal effects of these processes.

2.2. Methodology of testing

There are several methods of investigating thermophysical properties of moulding sands but no one is universal. Generally these methods belong to two categories.

- Methods of testing under conditions of a steady heat flow (a constant heat flux flowing through the selected moulding sand layer).
- Methods of testing under conditions of an unsteady heat flow through the selected moulding sand layer.

In the solution belonging to the first category, heating of the moulding sand layer (sample) by the heating element is used and then the directional heat flow is forced (unidirectional – for flat samples, or axially symmetrical – for cylindrical samples with the heat source situated in the axis). For the determination of the thermal conductivity (λ_2) one of the basic conduction equations are used. This equation describes the dependence between the thermal flux intensity (q), flowing through the moulding sand layer of a thickness („l'') related to the surface unit by the temperature gradient (at this thickness) – $(T_2 - T_1)$ and by the thermal conductivity coefficient, equation (3):

$$q = \frac{\lambda_2}{l} \cdot (T_2 - T_1) \tag{3}$$

The thermal conductivity coefficient is determined from the transformed equation (3). Since moulding sands are porous materials, on their conductivity decide: the thermal conductivity coefficient of the skeleton of the porous body structure (matrix) λs and of the medium filling pores λs (either liquid or liquid and gas mixture or gas only). In investigations of moulding sands, which are typical porous materials the so-called *effective coefficient of thermal conductivity* λsf is experimentally established.

Experimental determination of the thermal conductivity consists of: measurements of the temperature gradient on the sample cross-section, determining (either by measurements or by calculations) the value of the heat flux penetrating the sample, measuring the distance between layer edges (in which the temperature gradient occurs) and measuring the heat exchange surface.

Conductivity investigations under conditions of an unsteady heat flow (the second category) consists of recording and analysing the heating pathway of the moulding sand sample placed in the special mould, after pouring it with liquid metal and recording the casting cooling the sample thermal conductivity was preceded by the determination of the coefficient of temperature conduction (α_2), calculations of the coefficient of heat accumulation (b_2), followed by calculation of the thermal conductivity coefficient (λ_2) from equation (4):

$$\lambda_2 = (A + B \cdot C) \cdot m \tag{4}$$

where:

A, B – constants characterising the given measuring stand,

C – heat storage capacity of the tested material,

m – cooling rate.

Each of the symbols of equation (4) has the mathematically complex structure. The procedure, described in details in previous studies [2÷5], was applied in calculating the thermal conductivity coefficient.

2.3. Results of investigations

2.3.1. Conductivity measurements at the steady heat flow

The new experimental stand for investigations of the moulding sands thermal conductivity, under conditions of a steady heat flow, was built in the Faculty of Foundry Engineering AGH (Laboratory of Foundry Moulds Technology). This stand is adapted for moulding sands with organic binders. The solution is one of the variants of the concept of testing the thermal conductivity proposed by Poensgen [8]. These moulding sands specificity lies in the fact that after heating to a temperature above 300°C the organic binder destruction starts. This process ends at a temperature slightly higher than 500°C. The consequence of this process constitutes the sample (mould) decomposition, which renders difficult the testing procedure. This effect was taken into account in the designing works of the new experimental stand. The schematic presentation of the heating system structure of the sample with the unidirectional heat flow and the thermocouples system for measuring the temperature distribution is presented in Figure 1.

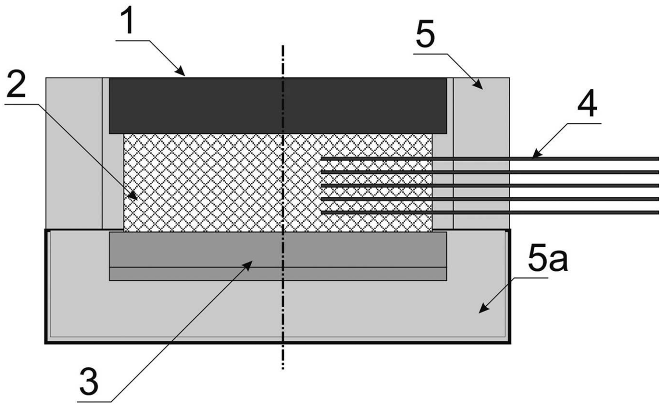

Fig. 1. Schematic presentation of the measuring system together with thermocouples placed in the sample: 1 – cooling plate, 2 – tested sample, 3 – controlled heating element, 4 – thermocouples, 5 – thermal insulation mounted before the measurement, 5a – stable thermal insulation

The heating system of the moulding sand sample (2) consists of the controlled heating element (3), cooling system (1), thermal insulation system (5 and 5a), thermocouples system (4), used for recording the temperature distribution in the measured sample and for control of the heating system. The heating system structure allows to obtain the needed temperature and the stabilised, unidirectional heat flow through the tested sample.

The measuring stand diagram is presented in Figure 2. The heating temperature is controlled by the industrial controller (Fig. 2 – element C). The electronic relay SSR was applied as the executing element – switching over the heating system supply. For measuring the current parameters during the sample heating the universal meter was used (Fig. 2 – element D). This meter was connected in series with the heating element – recording via the USB port – Sanwa 510a. Voltage measurements on the heating element were also performed. From the changes of the current intensity pathways, which was periodically switched on by the controller, the average current value was calculated, and then – on this bases – the power input of the heating element was also calculated.

The heat flow was oriented according to the designing assumptions of the experimental stand. The heat from the heating element was flowing through the lower surface of the moulding sand sample then through the sample itself and was 'directed' towards the upper plate, which was intensively water cooled. The directional heat flow was achieved due to: an application of the flat-shaped sample, thermal insulation of side surfaces of the sample with modern insulation materials and the application of the plate, which was intensively cooling the opposite side of the moulding sand sample.

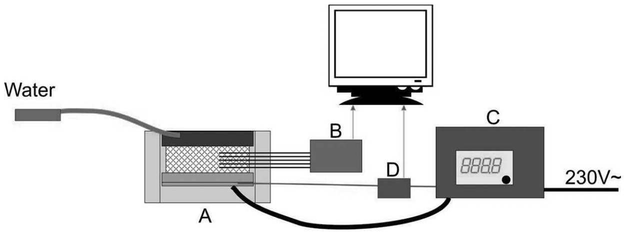

Fig. 2. Scheme of the measuring stand for investigating the thermal conductivity of moulding sands with chemical binders. Measurement under conditions of the steady heat flow

The heating of the heating plate was controlled by the temperature controller. To limit its corrosion, the plate was made of the acid resistant steel. Relatively large plate thickness enabled a uniform heating of the moulding sand sample on its whole surface. The thermocouple, type 'K', was installed in the lower part of the plate for controlling the heating system.

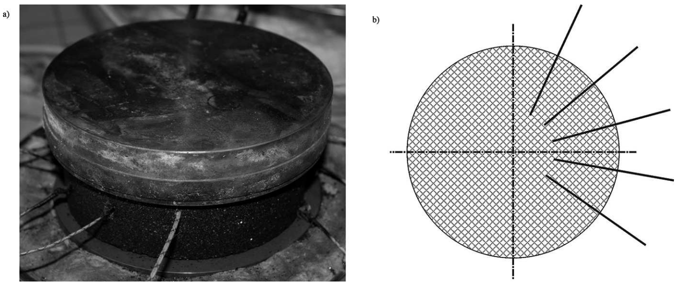

Fig. 3. a) Sample placed on the heating plate together with thermocouples and cooling plate – a) state before installation of the side thermal insulation, b) the way of installing measuring thermocouples

Temperatures in individual places of the sample were recorded by means of the multichannel measuring instrument, Agilent 34970A (Fig. 2. – element B). The way of installing measuring thermocouples is shown in Figures 1 and 3b. The typical temperature distribution in the sample, during the thermal conductivity testing is presented in Figure 4. Two periods are characteristic in the temperature pathway: the first – unsteady (initial heating) and the second – stabilised (steady). When the temperature stabilised itself in all measuring points, the current parameters of the heating plate were measured, since they were necessary in calculating the heat flux intensity. The temperature pathways are displayed on the computer in a real time, which simplifies the determination of the starting moment of recording the heating system current parameters.

These current parameters were used in calculation procedures of the heat flux intensity. These were parameters values at which the temperature zone in the sample is characteristic for the stabilised heat flow, it means the constant temperature gradient is maintained.

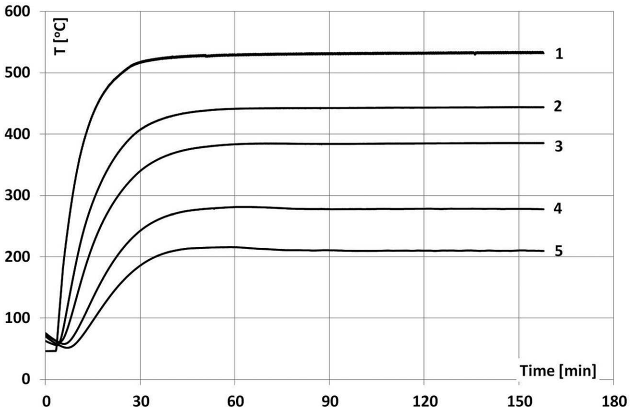

Fig. 4. Heating pathway of the moulding sand sample prepared with the application of furan resin as a binder. Recording in individual moulding sand layers.

2.3.2. Investigation results by the method of the steady heat flow

A series of measurements of the thermal conductivity of moulding sands with furan resin was performed. The matrix of the tested moulding sands was high-silica sand either fresh or reclaimed. Furanol FR75A resin in amounts of 0.8÷1.0% was used as a binder, while PTS acid as a hardener in amounts of 0.45÷0.55%. Investigations of moulding sands with graphite additions in amounts up to 10% in relation to a matrix as well as with steel shots additions in the same amount were also performed. Additionally, for comparison assessments of the matrix influence on the thermal conductivity, investigations of moulding sands with chromite and magnesite matrices were performed. Also for comparisons the moulding sand with inorganic binder – water glass, which was added in amount of 3.5%, was investigated. The moulding sand was prepared in the ester technology – with Flodur, as a hardener added in amount of 10%, in relation to the water glass amount.

All samples were prepared for measurements in the same way: before testing their thermal conductivity, they were dried at a temperature of 120°C for two hours. The dependence from the equation (3) was used in the developed measuring methodology of determining the thermal conductivity coefficient.

The instantaneous intensity of the heat flux generated by the heating plate and flowing through the sample was determined by means of the wattmeter. The heat flux intensity (q) was calculated as the ratio of the measured heating power to the contact surface: moulding sand sample/heating plate. The obtained results of the thermal conductivity of moulding sands with chemical binders, including sands with additions intensifying heat exchanging, are shown in Figure 5. Moulding sands were heated up to a temperature of app. 450°C. A higher temperature caused a destruction of moulding sand with resins, which renders difficult and – in practice – makes the proper measurement impossible.

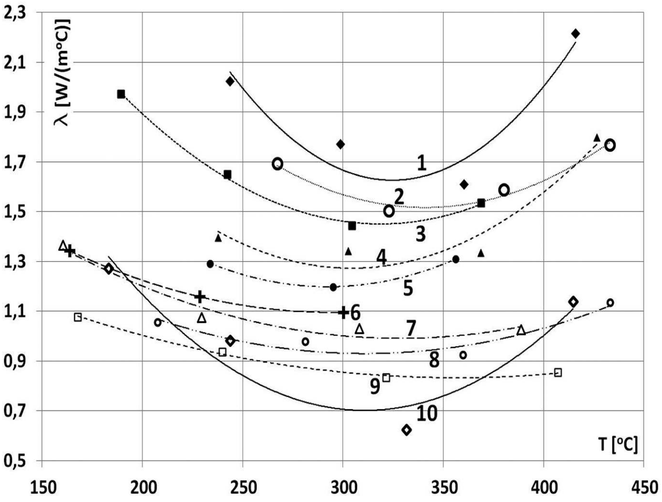

Fig. 5. Thermal conductivity of moulding sands of the modified composition based on a furan binder (Furanol FR75A) with a matrix: 1 – reclaim + 10% graphite + steel shot; 2 – reclaim + 10% graphite, ρ_o =1.5 g/cm^3; 3 – reclaim + 10% graphite, ρ_o =1.6 g/cm^3; 4 – reclaim + steel shot; 5 – reclaim + steel shot; 6 – moulding sand with water glass; 7 – reclaim + 5% graphite; 8 – chromite sand, ρ_o = 2.9 g/cm^3; 9 – reclaim, ρ_o =1.6 g/cm^3; 10 – reclaim, ρ_o =1.5 g/cm^3.

The analysis of the obtained results leads to the given below conclusions.

- In a similar fashion as in case of moulding sands with bentonite (which conductivity investigations are described in papers [2, 3]) in moulding sands with chemical binders a non-linear temperature influence on the thermal conductivity is also observed.
- The thermal conductivity minimum occurs at a temperature of app. 300÷350°C. Both at a lower and at a higher temperature the moulding sand conductivity is higher.
- A lower thermal conductivity have moulding sands unsatisfactory compacted (ρ_o <1.5 g/cm^3) prepared from the reclaim without additions.
- A compaction increase (porosity decreasing) leads to increasing of the thermal conductivity in case of all kinds of sands.
- The graphite introduction into the sand in amount of 10% (mass) increases the moulding sand conductivity nearly twice.
- Even higher conductivity can be obtained when, apart from graphite, steel shots (which increase the sand ability

for heat accumulation) are introduced into the moulding sand.

- Moulding sands with water glass are characterised by a higher ability of the thermal conductivity than moulding sands with organic binders (resin). The resin pyrolysis at relatively low temperatures causes decreasing of the temperature gradient and – in consequence – decreasing the heat flux penetrating into the mould.
- The matrix change from quartz into chromite, only slightly improves the thermal conduction ability of the moulding sand with furan resin. Similar effects causes an introduction of the magnesite matrix. Thus, this direction of looking for moulding sands of a high ability for the thermal conductivity is not the proper one.

2.3.3. Investigations under conditions of the unsteady heat flow

The method of determining thermophysical properties of moulding sands with chemical binders, proposed in this paper, is based on measuring the temperature zone of the system: casting – mould, by means of thermocouples placed in various measuring points. This method belongs to direct methods of testing the metal cooling and solidification in sand moulds [3]. The diagram of the measuring stand (experimental mould) is presented in Figure 6.

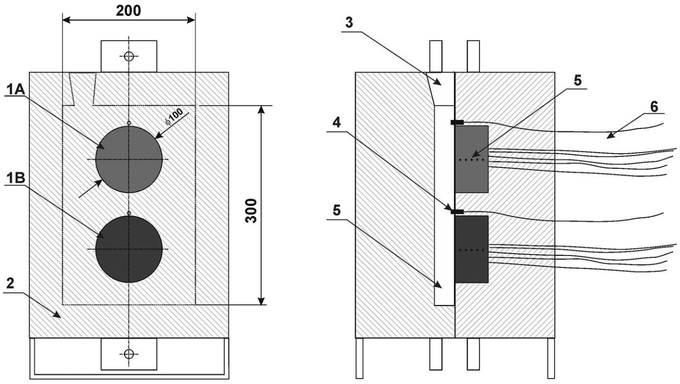

Fig. 6. Ideological diagram of thermal conductivity measurements of moulding sands directly in the mould: 1A, 1B – samples of the tested moulding sand, 2 – mould, 3 – gate, 4 – thermocouple ‘in casting’, 5 – plate casting, 6 – thermocouples in moulding sand samples

Two samples made of the tested moulding sand were placed in the mould. In each sample 4 thermocouples, allowing to record the heating process after pouring the mould with liquid metal, were placed. The recording of the casting cooling pathway is, in this method, necessary for calculations. Therefore in each measuring series the casting cooling was recorded by means of two thermocouples properly situated. The mould view with inserts made of the tested moulding sand is shown in Figure 7a. The casting with visible ‘traces’ of the tested inserts (of moulding sands with furan resin as a binder) are shown in Figure 7b.

Halves of the mould, made of the classic moulding sand, were dried at 220°C for 24 hours, in order to eliminate the influence of water vapours – from the wet moulding sand – on the obtained results.

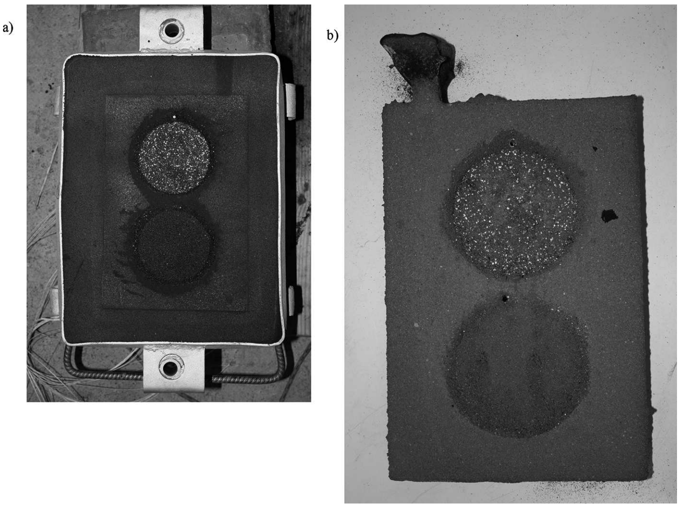

Fig. 7. a/ Mould for the thermal conductivity testing with two inserts made of the tested moulding sands with furan resin, b/ Test casting with visible ‘traces’ of the tested inserts

The casting of dimensions: 33×200×300 mm was made of grey cast iron and moulds were poured with metal of a temperature ~1400°C. The total recording of temperatures, both in the casting and in the mould, was performed in each test. The example is shown in Figure 8.

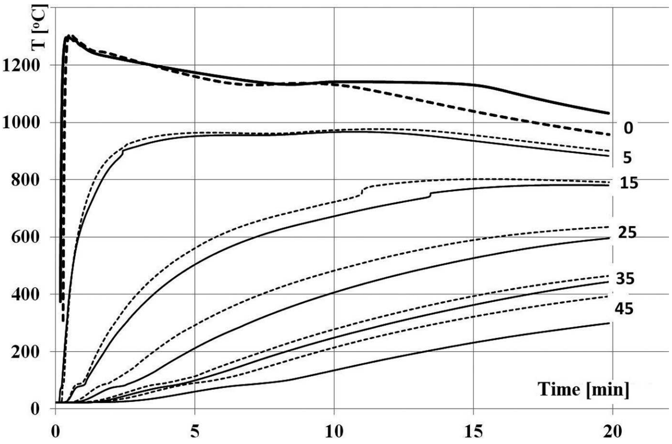

Fig. 8. Examples of the pathways of the iron casting cooling and moulding sands heating in samples for the determination of moulding sands conductivity under unsteady conditions. Dotted lines – moulding sand with the reclaim matrix, continuous lines – moulding sand with a reclaim + graphite (10%)

A temperature of the cooled casting (plate) was measured in a direct vicinity of the insert, which allowed to assess, approximately, the influence of the heat transfer of the moulding sand – used for making the insert – on the cooling time of the plate being in the vicinity of this insert.

The analysis of pathways shown in Figure 8 allows to notice that the casting solidification time of the furan moulding sand (matrix – reclaim) is significantly longer than the solidification time of the same moulding sand but containing additions of app. 10% of a graphite dust. These qualitatively described conditions were confirmed by the thermal conductivity results of the mentioned moulding sands. The lines in Figure 8 indicate distances between the measuring points and the contact surfaces: casting/mould.

The thermal conductivity results of four tested moulding sands, which represent sands which could be used for controlling the casting cooling rate, are listed in Figure 9. Moulding sands with organic binders (furan resin) are characterised by very similar pathways, in respect of the temperature influence on the thermal conductivity coefficient value.

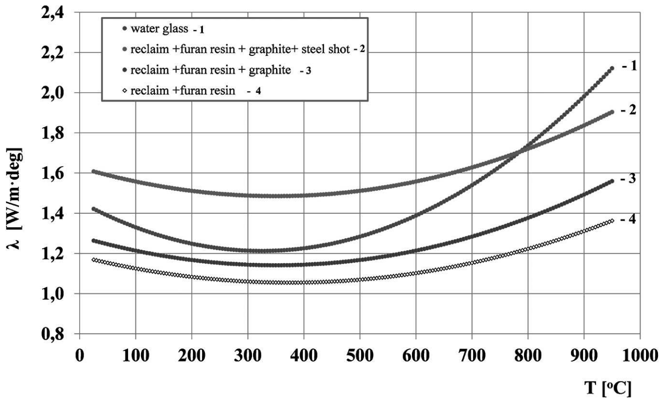

Fig. 9. Thermal conductivity of the selected group of moulding sands with additions increasing the sand ability for heat conduction. Investigations under conditions of an unsteady heat flow

The lowest conductivity reveals the moulding sand based on the reclaim matrix without any modifying additions. In a similar fashion as in the previously described tests results (conductivity under steady conditions), in these studies the conductivity minimum was also found at temperatures of approximately 300-400°C.

An introduction of additions increases the thermal conductivity of moulding sands. Already an introduction of 10% of graphite increases the thermal conductivity in a visible way. However, a significant increase of the conductivity is obtained after an additional introduction of steel shots. The thermal conductivity ability of such moulding sand is nearly twice as high as of the sand without any additions.

The completely different thermal characteristic have moulding sands with water glass. A lack of the 'internal heat source', which constitutes the resin pyrolysis, causes that the moulding sand with water glass has decisively better thermal conductivity, especially at the increased and high temperatures. At a temperature of approximately 900°C this conductivity is nearly twice as high. At slightly lower temperature in moulding sands with water glass melting of water glass occurs. To that effect a better joining of matrix grains by elastic bridges occurs, which probably facilitates the heat flow.

2.3.4. Derivation studies of furan moulding sands

Heating of moulding sands with organic binders leads to binders decompositions and heat emissivity. This is confirmed by derivative investigations of moulding sands with furan resin, the results of which are shown in Figures 10 and 11. Tests were carried out in the air, without the protective atmosphere. The samples mass losses start at a relatively low temperature, and after exceeding 300°C the pyrolysis process visibly accelerates (Fig. 10). This process is of an exothermic character, which confirms the temperature pathway in the DTA curve (Fig. 11).

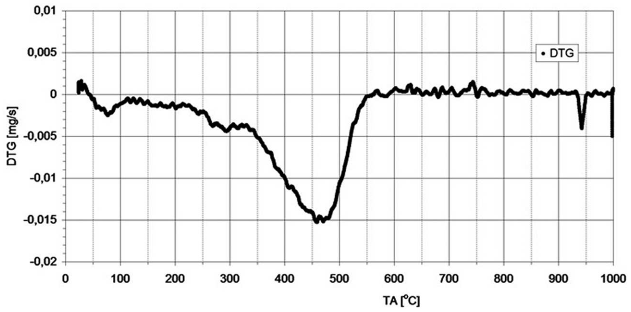

Fig. 10. Pathway of the sample mass change (moulding sand with furan resin as a binder) – DTG curve

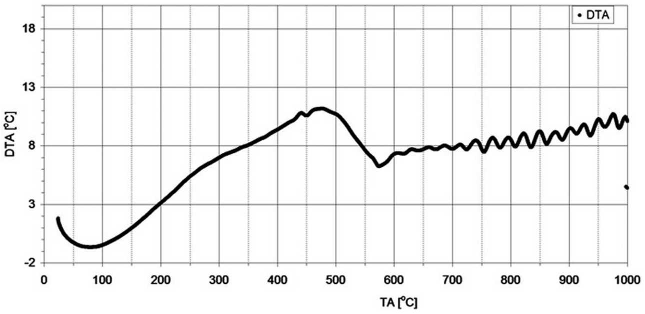

Fig. 11. Pathway of the sample temperature (moulding sand with furan resin as a binder) – DTA curve

The heat occurring during heating of furan moulding sands can be one of the reasons of the thermal conductivity decreasing at a temperature of approximately 300-400°C. Such decrease was found in the thermal conductivity investigations at steady and unsteady conditions of heat flow (Fig. 5) and (Fig. 9), respectively.

3. Conclusions

The thermal conductivity of moulding sands with binders, which are broadly applied at making medium and large castings, is very poorly known. Binders decomposition at a relatively low temperature renders measuring difficult and several investigation methods are not suitable for investigating moulding sands being in such state. The developed, new methodology of investigating the moulding sands conductivity – by means of the steady heat flow – allows to study this group of sands. The performed tests allowed determining the thermal conductivity in the range up to approximately 450°C. The minimum of the conductivity value at a relatively low temperature, (approximately 300-350°C) is probably related to the binder pyrolysis and heat emissivity, which disturbs and slows down the heat flow from the casting into the mould.

It was pointed out in investigations, that the conductivity increase can be achieved by introducing such additions as graphite or steel shot into moulding sands. A low conductivity of moulding sands with organic binders can prevent obtaining a fine structure castings. The conductivity assessment under conditions of an unsteady heat flow leads to similar conclusions. Moulding sands with organic binders reveal the lowest conductivity at a temperature slightly above 300°C. A much better conductivity characterises moulding sands with inorganic binder – water glass. The difference is specially visible at higher temperatures, above 500÷600°C.

A conductivity increase at the compaction degree increasing (which measure is the apparent density) is observed in all kinds of moulding sands.

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