A R C H I V E S O F M E T A L L U R G Y A N D M A T E R I A L S
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USEFULNESS OF FOUNDRY TOOLING MATERIALS IN MICROWAVE HEATING PROCESS

MOŻLIWOŚCI ZASTOSOWANIA W PROCESIE NAGRZEWANIA MIKROFALOWEGO MATERIAŁÓW DO BUDOWY OPRZYRZĄDOWANIA ODLEWNICZEGO

The paper describes preliminary examinations on establishing usefulness criteria of foundry tooling materials in the microwave heating technology. Presented are measurement results of permittivity and loss tangent that determine behaviour of the materials in electromagnetic field. The measurements were carried-out in a waveguide resonant cavity that permits precise determination the above-mentioned parameters by perturbation technique. Examined were five different materials designed for use in foundry tooling. Determined was the loss factor that permits evaluating usefulness of materials in microwave heating technology. It was demonstrated that the selected plastics meet the basic criterion that is transparency for electromagnetic radiation.

Keywords: microwaves, permittivity, loss tangent, loss factor, foundry tooling

W pracy podjęto wstępne badania nad ustaleniem kryteriów oceny przydatności materiałów do budowy oprzyrządowania odlewniczego, przewidzianego do zastosowania w technologii nagrzewania mikrofalowego. Przedstawiono wyniki pomiarów przenikalności elektrycznej oraz tangensa kąta stratności, które określają zachowanie materiałów w polu elektromagnetycznym. Pomiary przeprowadzono na stanowisku falowodowej wnęki rezonansowej, która umożliwia precyzyjne wyznaczenie metodą perturbacyjną wymienionych parametrów. Badaniom poddano pięć różnych materiałów przewidzianych do zastosowania w budowie oprzyrządowania odlewniczego. Określono współczynnik stratności, który pozwala, na ocenę przydatności materiałów w technologii nagrzewania mikrofalowego. Wykazano, że wybrane tworzywa sztuczne spełniają podstawowe kryterium, jakim jest transparentność dla promieniowania elektromagnetycznego.

1. Introduction

The microwave technology finds its application in variable fields of science, industry and medicine. Searching for possibly most effective ways of drying and hardening moulding materials used in foundry practice contributed to increasing the interest in microwave radiation. Thanks to its specificity, this way of heating can constitute a modern, economical segment in the processes of mechanisation, automation and modernisation of a foundry. This results in more and more common use of electromagnetic radiation in foundry practice, which makes an innovative alternative for traditional methods [1]. Volumetric nature of microwave heating brings a lot of benefits, in particular improves effectiveness of heating, reduces energy consumption, reduces the process time and permits obtaining good quality products [1,2]. Experimental results of microwave hardening of moulding sands with both inorganic (water glass, BioCo) [3-5] and organic binders (oils) [6] justify undertaking a research on industrial implementation of the microwave heating process. Implementing the microwave heating process of moulding and core sands on industrial scale is difficult due to a shortage of the information necessary at designing and manufacturing the foundry equipment. The restrictions result, first of all, from the necessity to use suitable materials that are transparent for microwave radiation, resistant to wear and high temperature, as well as guarantee effective removing the created gases [1]. Most of the materials presently used for foundry tooling do not meet the criterion of transparency for microwave radiation. This criterion is only met by a specific, limited group of plastics, namely by dielectric materials [7]. The presented research was aimed at assessing, with respect to the criterion of transparency to microwave radiation, usefulness of some commercially available foundry materials for application in the microwave heating technology.

2. Foundry tooling

Foundry tooling used for preparation of disposable moulds includes patterns, core boxes, pattern plates and moulding boxes. The materials used for foundry tooling should guarantee required shape accuracy and dimensional stability, as well as be characterised by low adherence to the sandmix

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and by high wear resistance [8]. In general, typical materials used for foundry tooling are wood, plastics and metals. Their selection depends, among others, on the casting complexity degree and production volume [9,10].

2.1. Selection strategy of foundry tooling materials for microwave heating process

When designing foundry tooling subject to microwave radiation, the prerequisite is ensuring efficient and effective heating of moulding and core sands. The selection procedure of materials for foundry tooling and their treatment process should permit meeting all the requirements posed to the tooling designed for a specific technology of heating moulding and core sands. In microwave heating processes, this selection is determined by basic functions, assumptions, purposes and variables presented in Table 1. The foundry tooling is to execute individual functions conditioned by meeting the definite presumptions [11].

TABLE 1
Functions, assumptions, purposes and variable parameters of designed foundry equipment to be used in microwave heating processes

Functions of foundry tooling	Giving required shape to moulding sand, manufacture of cores
Assumptions	Transparency to microwaves, accuracy of shape and dimensions, dimensional stability, high wear resistance, low adherence to moulding sand, effective degassing, thermal resistance
Purpose	Minimization of tooling costs, maximization of moisture permeability
Variable parameter	Material selection

Usefulness of a given material for microwave heating is decided mostly by transparency to electromagnetic radiation, so the best materials for foundry tooling are those characterized by best transmission capacity of microwave radiation. Choice of a material transparent to microwave radiation should make possible selecting further treatment processes, as well as shape and geometrical relations of the foundry tooling. The presented research work was basically limited to analysis of the most important assumption, i.e. the criterion of the most profitable transparency to microwave radiation of the materials selected from among structural materials meeting this requirement. Within the subsequent, planned research works, the materials selected at this stage will be subject to analysis from the viewpoint of treatment processes of the foundry tooling components.

2.2. Foundry tooling materials

Considering various selection criteria, the materials designed for foundry tooling to be used in the microwave heating process can be classified on the grounds of their electrical conductivity. With this respect, three groups of materials can be distinguished: lossless dielectrics with zero conductivity, lossy dielectrics and high-conductivity dielectrics [12]. In the materials demonstrating dielectric properties, an external electric field causes polarization. Then, electric charges appear on the surface of a real dielectric, creating electric field with phase displacement δ in relation to the field causing polarization and directed conversely to the field causing polarization. Displacement of the charges in the dielectric volume results in creating dipole moments that disappear at the moment of removing the dielectric material from the electric field area. Tangent of the δ angle ($tg\delta$), called the loss tangent, is a measure of lossiness of the material medium. The higher lossiness, the larger is the $tg\delta$ value [7,13]. Distinguished are various kinds of dielectric polarization: elastic polarization (electron or ionic induced) and relaxative polarization (dipole, ionic relaxative, spontaneous or macroscopic). The phenomena of dipole and ionic relaxative polarization are of significant importance, since they are accompanied by energy losses resulting from charge displacements in spite of the acting medium resisting forces and chaotic thermal motion of atoms [13]. Macroscopic properties of dielectrics in alternating electric field are described by relative complex permittivity ε_r [14] described by the formula (1):

$$\varepsilon_r = \varepsilon' - j\varepsilon'' \tag{1}$$

where: ε' – real component of relative complex permittivity, ε'' – imaginary component of relative complex permittivity.

It should be noted that this property is not a material constant, because it changes depending on the electromagnetic wave frequency. Thus, depending on properties of the electric field, the material can be treated as a lossless dielectric, lossy dielectric or a well conducting medium [12]. The real component of relative complex permittivity expresses ability of a material to accumulate energy and the imaginary component is responsible for ability of a dielectric material to dissipate the energy accumulated in the electric field, i.e. to generate energy losses [13]. When selecting materials to minimize dielectric losses, one can use the loss factor L described by the formula (2). Its value is directly proportional to the amount of energy dissipated by the dielectric in variable electric field [7].

$$L = \varepsilon_r tg\delta \tag{2}$$

3. Test stand

Measurements of dielectric permittivity ε_r and dielectric loss tangent $tg\delta$ are made in various ways, depending on material type, size and shape of specimens, frequency and bandwidth of operating frequency, as well as on expected range of the measured quantities. For measurements of dielectric materials used in the foundry processes, the perturbation method was chosen. This method makes it possible to take measurements within wide temperature and humidity ranges, as well as to determine precisely the imaginary component of relative complex permittivity ε_r and the dielectric loss tangent $tg\delta$ within microwave frequencies. In the perturbation method, shape of the examined specimens is unimportant, if only their volume is much smaller than volume of the resonant cavity (Fig. 1).

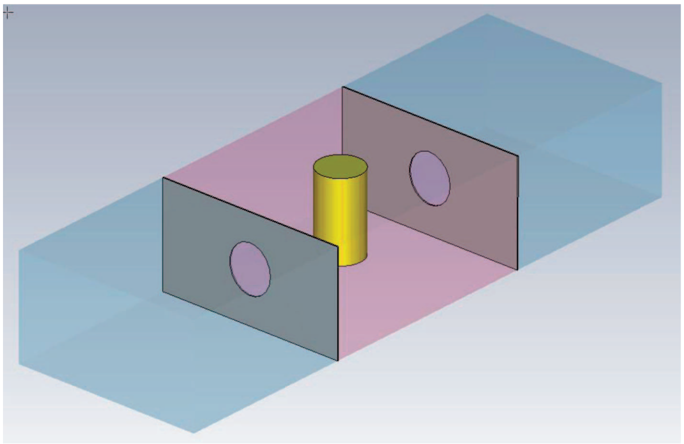

Fig. 1. Schematic presentation of rectangular waveguide resonator with examined specimen

The basic phenomenon used in the perturbation method are changes of resonance frequency and quality of the resonant cavity, caused by introducing lossy materials inside the resonator. In the case of measuring electrical properties of non-magnetic materials, a small specimen of the examined material is placed in the cavity at the place where the electric field intensity reaches its maximum [14]. Then, resonance frequency f and quality Q of the cavity change, as capacitance of the resonator cavity changes. Quality of the resonant cavity can be determined by measuring width of the resonance curve on the ground of the relationship (3) [14].

$$Q = \frac{f}{\Delta f} \tag{3}$$

where: f – resonance frequency, $\Delta f = f_g - f_d$ – difference between upper f_g and lower f_d frequency for the 3 dB bandwidth.

The real ε' and the imaginary ε'' components of relative complex permittivity ε_r can be determined from the relationships (4) and (5) that permit also calculating the loss tangent $tg\delta$ (6) [14].

$$\varepsilon' = \frac{V_c\,(f_0 - f_s)}{2V_s f_s} + 1, \tag{4}$$

where: f_s – resonance frequency of the cavity with a specimen, f_0 resonance frequency of the cavity, V_c – volume of the resonant cavity, V_s – volume of the specimen.

$$\varepsilon'' = \frac{V_c}{4V_s}\left(\frac{1}{Q_s} - \frac{1}{Q_c}\right), \tag{5}$$

where: Q_s – quality of the cavity with a specimen, Q_c – quality of the cavity.

$$tg\delta = \frac{\varepsilon''}{\varepsilon'} \tag{6}$$

In the measurements of dielectric permittivity ε_r and dielectric loss tangent $tg\delta$ using the perturbation method, applied was the measuring stand composed of a high-frequency signal source, cubicoidal resonator, diode array detector and oscilloscope. The resonator was made in form of a waveguide resonant cavity 86 mm×43 mm×100 mm, with basic field mode TE_{101}, transmission-connected in the waveguide line and coupled through round bores dia. 26 mm in the resonator walls.

4. Measurements of permittivity and loss tangent

Materials for examinations were selected by analysis of the diagram [7] comparing dielectric loss factors and mechanical strength of dielectric materials. Rigid polymer foams, some polymers and ceramic materials (quartz glass, Al_2O_3) are characterised by the lowest lossiness.

From among the analysed materials, five grades were selected for examinations: two kinds of polytetrafluoroethylene PTFE (new and recycled teflon), polyamide PA, ceramic mat based on refractory fibres made of aluminium oxide and silica, as well as a composite material composed of epoxy resin and cotton fabric. Of all the engineering materials, polymer foams deserve a special attention, since, due to their specific structure (filling with air transparent to electromagnetic radiation), they demonstrate the desired dielectric properties, the best ones with respect to transparency to electromagnetic radiation. Properties of the selected, commercially available polymer foam are: dielectric permittivity $\varepsilon_r = 1.05$ and loss tangent $tg\delta$ <0.0002 (for $f = 2.5$ GHz). Therefore, structural polymer foam can be a comparative reference material for the other materials designed for foundry tooling. Permittivity and dielectric loss factor of dielectric materials depend on temperature, electric field strength, humidity and frequency [13]. Measurements of dielectric properties of the selected materials were taken at 20°C and air humidity 60%. Before taking measurements of dielectric parameters, measured was resonance frequency and quality of empty resonant cavity. Examinations were carried-out on cylindrical specimens dia. 20 mm (dia. 18 mm for composite specimens) and 33 mm long (32 mm for composite and polyamide specimens).

5. Results

Results of permittivity and loss tangent measurements for the selected materials suggested for foundry tooling are given in Table 2. The examinations were carried-out on three specimens of each material. In the table, given are arithmetic averages of individual measurements.

TABLE 2

Results of permittivity and loss tangent measurements

	Teflon	**Ceramic mat**	**Composite material**	**Teflon recycled**	**Polyamide**
ε_r	2.043	1.451	3.469	2.054	2.882
$tg\delta$	0.0011	0.0087	0.0490	0.00095	0.00993
L	**0.0022**	0.0126	0.1701	**0.0020**	0.0286

The obtained measurement results of permittivity and dielectric loss factors indicate that, with regard to transparency to microwaves, both new and recycled teflons are characterised by the best dielectric properties; their loss factor L being 0.0022 and 0.0020, respectively. Structural polymer foam is characterised by lower transparency to microwave radiation. However, considering the condition of suitable mechanical strength and wear resistance, polytetrafluoroethylene foam is characterised by much higher values [7]. From among the examined materials, composite material of epoxy resin and cotton fabric is distinguished by the largest dielectric losses.

6. Conclusions

Conclusions resulting from analysis of the measurement results of permittivity ε_r and loss tangent $tg\delta$ of dielectric materials designed for foundry tooling are as follows: 1. Using a waveguide resonant cavity stand permits preliminary evaluation of foundry tooling materials designed for microwave heating technology. 2. The materials characterised by the lowest lossiness are new and recycled polytetrafluoroethylene (teflon) that are selected for further examinations with respect to mechanical and application properties, as well as to their forming ability. 3. The composite material of epoxy resin and cotton fabric is characterised by the highest loss factor that shows its high susceptibility to absorbing microwave radiation and restricts its usefulness for possible application in manufacture of foundry tooling for microwave heating technology. 4. Knowledge of the loss factor ($L = \varepsilon_r\ tg\delta$) permits selecting a material designed for foundry tooling used in microwave heating processes.

REFERENCES

[1] K. Granat, D. Nowak, M. Stachowicz, Archives of Mechanical Technology and Automation **30**, 19-27 (2010) (in Polish).

[2] S.J. Kowalski, K. Rajewska, A. Rybicki, Physical basics of microwave drying, Publishing House of Poznan University of Technology, Poznań 2005 (in Polish).

[3] M. Stachowicz, K. Granat, D. Nowak, METALURGIJA **52**, 169-172 (2013).

[4] P. Jelinek, Development of inorganic binders for dehydrative microwave hardening, Conference Materials, VIII FOUNDRY CONFERENCE TECHNICAL 2005 (in Polish).

[5] B. Grabowska, M. Holtzer, Arch. Metall. Mater. **54**, 427-437 (2009).

[6] M. Stachowicz, K. Granat, M. Pigiel, Arch. Foundry Eng. **8**, 129-132, (2008).

[7] M. Ashby, H. Shercliff, D. Cebon, Materials Engineering, vol. 2, Publishing House Galaktyka Sp. z o.o., Łódź 2011 (in Polish).

[8] M. Perzyk, S. Waszkiewicz, M. Kaczorowski, A. Jopkiewicz, Foundry Practice, Publishing House ”Wydawnictwa Naukowo-Techniczne”, Warsaw 2000, 2004 (in Polish).

[9] T. Piwoński, Modeller's, Moulder's and Coremaker's Handbook, Publishing House ”Wydawnictwa Naukowo-Techniczne”, Warsaw 1977 (in Polish).

[10] K. Błaszkowski, R. Dembczyński, M. Feld, J. Galiński, Design principles of technological tooling, Publishing House ”PWN”, Warsaw 1981 (in Polish).

[11] M. Ashby, H. Shercliff, D. Cebon, Materials Engineering, vol. 1, Publishing House Galaktyka Sp. z o.o., Łódź 2011 (in Polish).

[12] W. Michalski, Basics of Electromagnetic Field Theory, part II, Electromagnetic waves, Publishing House of Wroclaw University of Technology, Wrocław 2009 (in Polish).

[13] M. Lisowski, Measurements of resistivity and permittivity of solid dielectrics, Publishing House of Wroclaw University of Technology, Wrocław 2004 (in Polish).

[14] J. Sheen, J. APPL. PHYS. **102**, 014102 (2007).

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