

Ceramic Mould Internal Structure Anomalies in the Lost Wax Process

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Received 10.03.2014; accepted in revised form 30.03.2014

Abstract

The paper analyzes the structure of the ceramic mould, which include discussion about its structure creation. The results of research relate to the strength of the ceramic mould and its thermophysical properties.

Structural anisotropy was found and its influence on the mould surface morphology depending on its position with respect to the sprue in the assembly set. The paper also presents evaluation of microgeometry of patterns, ceramic mould and casts produced in a joint production process.

Last part includes the results of the fractal dimension measurements of ceramic mould cross-sections. The analysis was based on the mould porosity. For the analyzed structures the percentage of pores and linear fractal dimension was determined, using the line counting dimension method (LCD), which is a modification of box counting dimension method (BCD).

Keywords: Ceramic mould, Anisotropy of ceramic mould properties, Fractal dimension, Heat transfer coefficient

1. Introduction

Studies have shown that the ceramic moulds surface microgeometry is a function of the pattern surface state, viscosity and surface tension of the liquid ceramic mould material, contact angle θ , velocity v , pressure h_k - fluidization parameters, during application of the first liquid layer and the liquid ceramic mould material imposing on it loose ceramic mould material with grain size from 0.1 mm to 0.15 mm. It can be concluded from this that the quality of reproduced pattern is mainly related to the process of forming the first layer of ceramic mold. Distribution of loose ceramic mould grains on different layers of the assembled set (Fig. 1) relative to the sprue (WG), has the effect of formation anisotropy of physical properties of the multilayer ceramic mould. Achieved mould structure, subjected to thermal loads in various

stages of lost wax casting, determines the dimensional and shape accuracy and micro-geometry of the casts. For casting quality the way of pouring the metal in to the mould and the phenomena observed in the metal which fills ceramic mould. It is also important to correctly choose mould materials, so the correct determinations of the coefficient of heat transfer [1]. This determines the time of metal solidification in a mould, which can be estimated [2]. The strength of the mould, its expansion and coefficient of permeability it is also important.

For the analysis of the discussed factors porosity distribution should be assessed. This will give the opportunity to assess the correlation in a "wax pattern – ceramic mould - precision cast". Checking the condition of the castings surface can help in choosing the parameters for manufacturing of specific casts.

Studying ceramic mould construction by using fractal dimension to evaluate the porosity and anisotropy of these moulds

is new approach to this problem, extending the scope of knowledge of the lost wax casting.

2. Influence of ceramic mould on its microgeometry

Anisotropy of the structure and properties of the multilayer ceramic mould are connected with methodology of dipping in the ceramic mould material and imposing on it a loose ceramic material. The liquid ceramic mould material after dipping in it the pattern assembly set (and later partially made mould) is distributed over the surface by rotating and emerged assembly set, which is also doing swinging movements. Imposed loose ceramic grain is affected the gravity which causes shifting of individual grains in a liquid ceramic mould material. The process takes about 1 to 2 minutes, depending on the ambient temperature. Consequently mould on different surfaces has various proportions of the liquid ceramic mould material with respect to the loose ceramic grains. Finally, after hanging assembly on the conveyor the side and bottom surfaces have thinnest walls, and on the upper surfaces of the thickest wall of the ceramic mould. These walls vary in average thickness of about 1 mm, resulting in variations of the ceramic mould properties in its different locations.

Moulds shown in Figure 1a were prepared under production conditions for research purposes and the mould shown in Figure 1b have been used in the actual production process. They were made on a pattern of a mixture of materials which include - paraffin, stearin, and polyethylene wax. The binder used is called Ludox SK (combining colloidal silica and soluble polymers) alternating with ethyl silicate. The ceramic material was crystalline quartz.

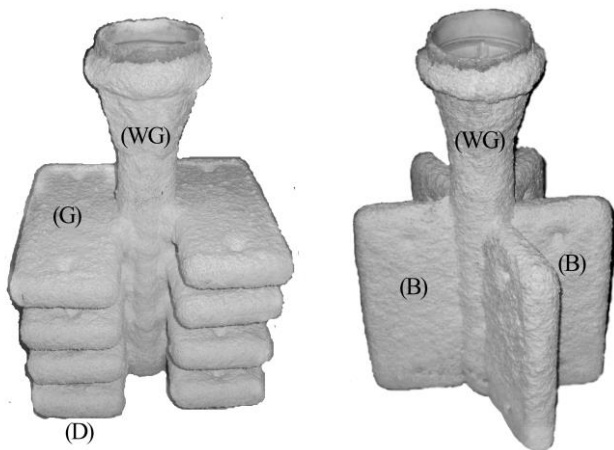


Figure 1. Ceramic mould used in the study: a) research mould, b) production mould,

The test specimens were cut in the way to obtain full inside walls of the mould:

- 1) Surface (B) - parallel to the axis of the sprue (WG),
- 2) Surface (G) - the upper perpendicular to the axis of the WG,
- 3) Surface (D) – the bottom perpendicular to the axis of the WG.

Shown in Figures 2 and 3 dependencies results from the analysis of multiple measurements of the parameter R_a carried on patterns and moulds used in the production and obtained in the casting process. To evaluate the surface parameters digital profilometer Perthen Mahr S3P was used. Due to the nature of micro-geometry measurement of precision casting moulds and casts detailed analysis was performed for each specimen. Outstanding values were discarded using the criterion of three sigma or analytically based on the difference of measured values from the arithmetic mean.

The data shown in Figure 2 was obtained from measurements of surface irregularity by R_a parameter confirm the morphology variation of the ceramic mould surface.

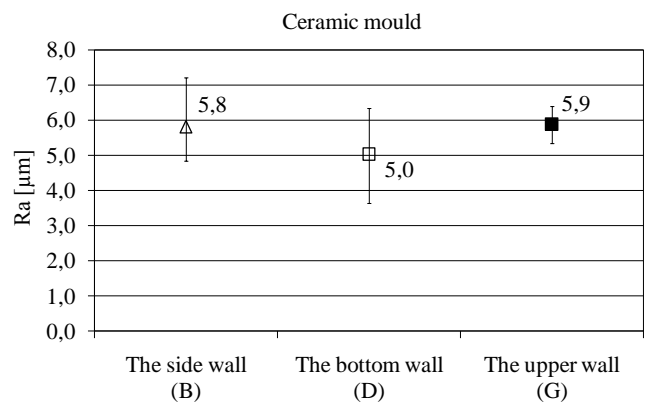


Figure 2. Microgeometry of ceramic molds wall surface examined by the parameter R_a

Summary shown in Figure 3 is prepared for wall (B) the ceramic mould of Figure 1b, pattern made from paraffin - stearin and the resulting cast.

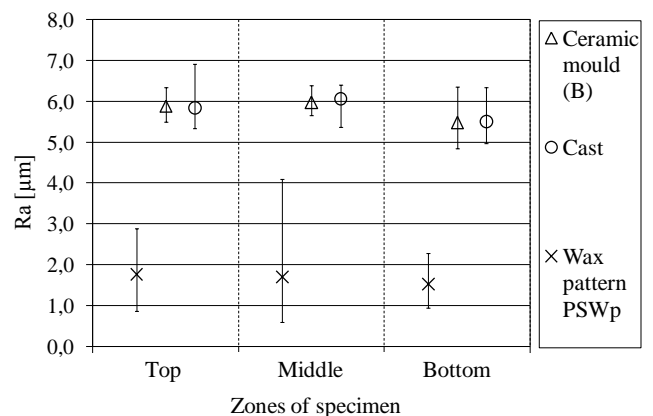


Figure 3. Surface microgeometry: 1) pattern, 2) a side wall surface (B) the production ceramic mould, 3) cast

From Figure 2 it is possible to deduct that that the top wall (G) has a stable surface, and the remaining walls have quite large variations of R_a values. This is consistent with results of previous studies on the density and thickness of the ceramic mould [3].

It has been found that there is density variation of the wall (B) along its height. The highest density was found in a wall (G). The roughness of the bottom wall (D) is less than the roughness of the walls of the upper (G) and side wall (B), with similar measurement uncertainty.

Shown in Figure 3 the results of the patterns R_a evaluation are characterized by a rather high measurement uncertainty due to the variability of the production parameters. In the case of casts, a lower roughness is observed at the bottom. In this area, the ceramic mould has a lower porosity, a greater thickness and consequently a lower roughness.

3. Fractal analysis

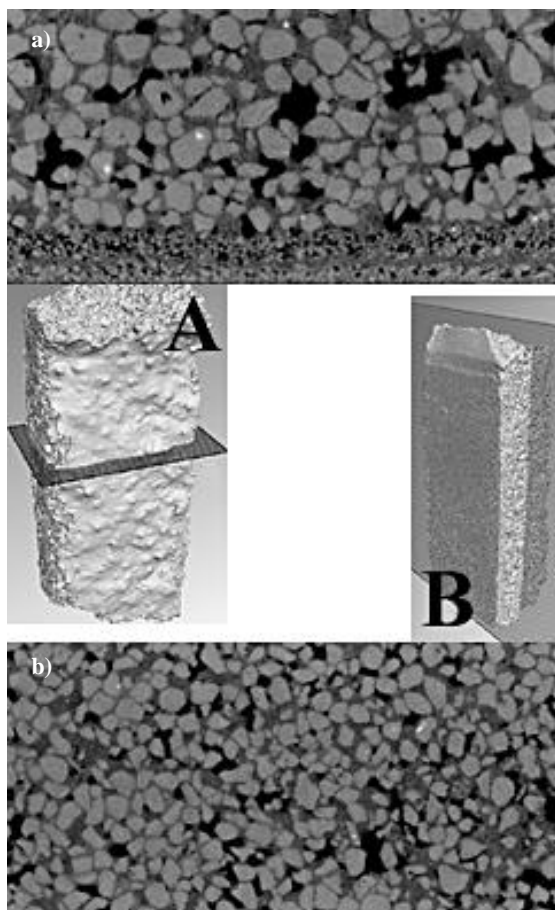


Figure 4. Transverse structure of the ceramic mould: a) cross-section A, b) cross-section B

Based on data obtained in the prior work [3], bending strength R_g was conducted on specimens cut from currently investigated ceramic moulds. Analysis of measurements made by three-point bending showed a significantly lower value of R_g on the surface (B) than on the surface (D) and (G).

The observed anisotropy of the ceramic moulds properties and discussed features of a ceramic mould allow defining the parameter of the total porosity. This parameter can be estimated using the methodology with usage of the ceramic mould cross section image analysis performed on computer tomography equipment Metrotom 800 (cross sections A and B shown in Figure 4).

Analyses were performed with usage of fractal dimension. The concept of fractal dimension can be used in welding [4] to describe structural changes occurring in the heat affected zone. In a similar way, it is possible to assess the percentage and distribution of pores in mould walls cross sections. Cross section of mould side wall (B) was used, which was characterized by the largest thickness variety. This differentiation is due to uneven distribution of loose material with a coarser ceramic grain.

The analysis of fractal structures was made on mutually perpendicular cross sections marked on Figure 4.

Measurement of fractal dimension was based on linear modification of the box counting dimension (BCD), allowing a thorough scan of the analyzed structure. The method used for determining the fractal dimension is presented in the item [4]. In order to determine of the fractal dimension, it was necessary to use computer processing of structures images. Digital images of structures having dimensions of 1024 x 512 pixels was subjected to computer processing to get binary images of the pores which are visible in cross-sections (Figure 5).

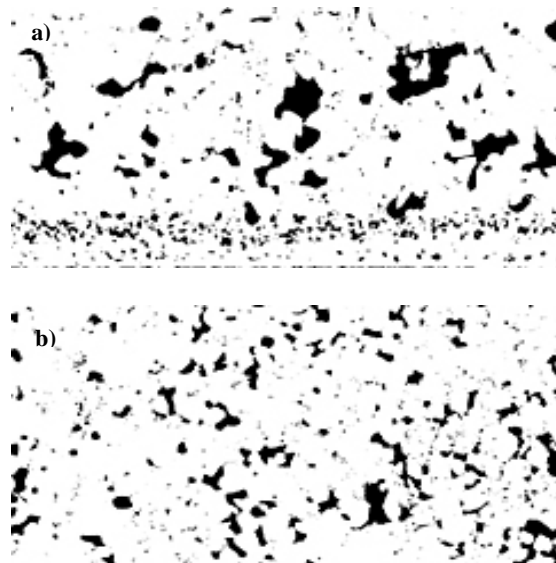


Figure 5. Binary images of porosity in the studied structures: a) cross-section A, b) cross-section B

In the context of image analysis and fractal analysis it was possible to determine the percentage of porosity in the analyzed structures (Table 1, Fig.6) and the linear fractal dimension D_1 in two perpendicular scan directions: horizontal – X and vertical - Y.

Table 1. The percentage of pores in the studied structures

Structure (cross-section)	A	B
Percentage	12,45 %	10,23 %

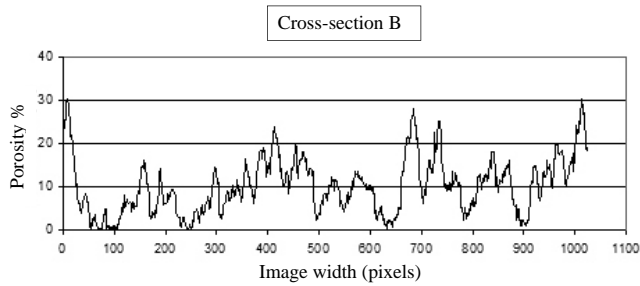


Figure 6. Changes in porosity - view B

Table 2 shows the cumulative results of determining the fractal dimension for the analyzed structures, and Figure 7 shows an example graph showing the change in fractal dimension in section B and the scanning direction X.

Table 2. Fractal dimension of analyzed structures

Structure (cross-section)	Fractal dimension $D_{l\ min} / D_{l\ avg} / D_{l\ max}$ (scan - direction X)	Fractal dimension $D_{l\ min} / D_{l\ avg} / D_{l\ max}$ (scan - direction Y)
	The range of fractal dimension $D_{l\ max} - D_{l\ min}$	The range of fractal dimension $D_{l\ max} - D_{l\ min}$
	0 / 0,5678 / 0,7957	0 / 0,5774 / 0,9018
A	0,7957	0,9018
B	0 / 0,5014 / 0,7835	0,3783 / 0,5703 / 0,7057
	0,7835	0,3274

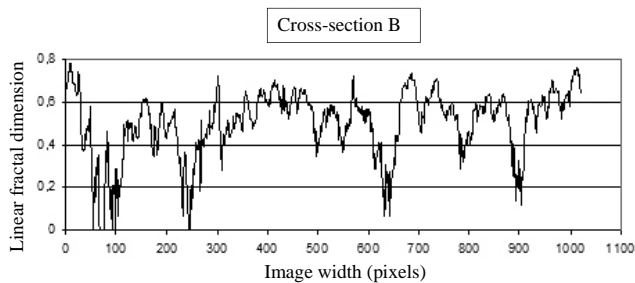


Figure 7. Fractal dimension D_l - cross-section B, the scan direction X

Complementing the measurements are graphs showing the absolute value of the difference in fractal dimensions $D_{lX} - D_{lY}$ (anisotropy of fractal dimension for scanning directions X and Y) in various points of binary images examined structures, shown in Figure 8.

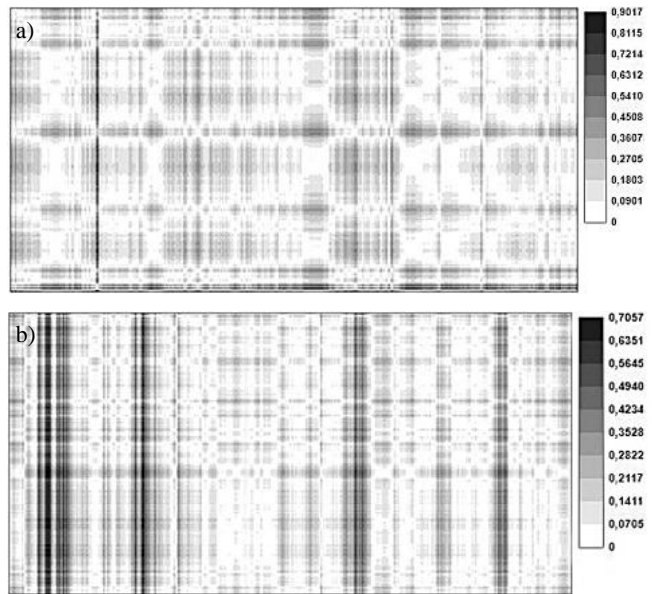


Figure 8. Anisotropy of fractal dimension $|D_{lX} - D_{lY}|$ examined structures a) cross-section A, b) cross-section B

Analyzing the results of fractal dimension measurements, it was found that in case of the examined cross sections the fractal dimension changes are relatively large. The largest range of variation was found for the cross section A (0.9018 for scanning direction Y), the smallest of cross section B (0.3274 for scanning direction Y). The differences between the average values calculated for the fractal dimension perpendicular to the scan direction are 0.0096 (cross section A) and 0.0689 (cross section B). For the cross section B absolute value of the difference between fractal dimensions $D_{lX} - D_{lY}$ is between 0-0,7057, and for the cross section A in the range 0-0,9017.

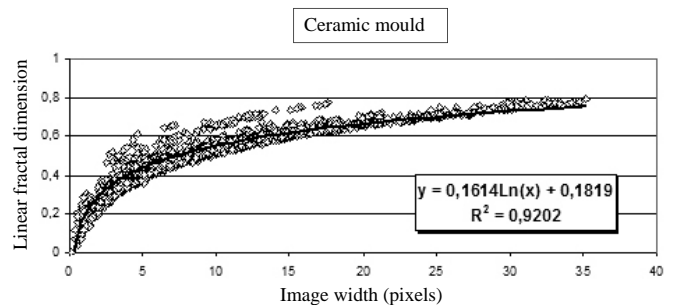


Figure 9. Fractal dimension D_l in function of porosity

Based on the rules for determining the fractal dimension it's possible to deduce that the greater part of the analyzed element of the structure, the greater the value of the fractal dimension. Figure 9 shows the dependence of the fractal dimension on the percentage of pores in the analyzed structures of the ceramic mould.

3. Thermophysical properties of ceramic mould

Thermal deformations of the ceramic mould in a lost wax method occur most frequently in mould heat treatment phase during and during solidification of casts. This type of deformation is affected by the mould porosity and the materials from which it is made. Obtaining a complete characterization of the properties of the mould is highly difficult due to undetermined occurrence of the mutual interactions between the liquid metal and mould, the phenomena in the mould and shape of the internal structure of solidifying cast.

It is important to determine the thermo-physical properties of the ceramic mould - thermal expansion and heat transfer coefficient. Expansion of ceramic mould specimen under a load in function of temperature is discussed in [5].

Study leading to the determination of the heat transfer coefficient should be carried out under conditions similar to those in the actual mould during the pouring liquid metal. For correctly shaped ceramic moulds, these tests were carried out by different authors and their selected results presented in [6].

In the study made by the author, determination of heat transfer coefficient λ was carried out according to the dependency set for a multi-layered cylindrical wall. Measuring position which was used in the study was similar to that proposed in [7]. As the heating element a sylith rod was used, which is placed under a cylindrical specimen. Temperature and adjustable power P was measured. The value of heat transfer coefficient λ of the cylindrical ceramic mould specimen was calculated from equation (1):

$$\lambda = \frac{P \ln \frac{d_2}{d_1}}{2\pi L(T_1 - T_2)} \left[\frac{W}{m \cdot K} \right] \quad (1)$$

where:

P - power released by the heating element [W]

d_1 - the inner diameter of the sample [m]

d_2 - the outer diameter of the samples [m]

L - heating length of the heating element [m]

T_1 - the inner surface temperature of sample [K]

T_2 - the temperature at the outer surface of the sample [K]

The tests were performed on specimens from ceramic moulds consisting six layers alternately made. The first, third and fifth layer of liquid ceramic mould material was applied without the addition of colloidal silica and latex polymers. On the second, fourth and sixth layer liquid ceramic mould material with ethyl silicate was applied. Powdered SiO_2 was used. Specimens were diversified by loose ceramic mould material grain size.

At each layer of *Specimen 1* filling SiO_2 was applied with grain 0.1 mm, while for *Specimen 2* filling material SiO_2 was with grain 0.5 mm was used.

The results of tests on an experimental station for the heating power $P = 0.20$ kW, defined as the average of several measurements taken at intervals of 3 minutes were as follows:

- *Specimen 1*: $\lambda_{\text{avg.1}} = 0.64$ W/m·K

- *Specimen 2*: $\lambda_{\text{avg.2}} = 0.70$ W/m·K □

It can be concluded that in the examined specimen heat transfer coefficient is relatively small.

3. Conclusions

The anisotropy of ceramic moulds properties is affected by the unevenly distributed portions of liquid ceramic mould material. It is possible to observe the movement of the loose grains of the ceramic mould material relative to the liquid ceramic mould material. For these reasons, it is important to quantitatively estimate the porosity and its distribution in the mould. The porosity of the ceramic mould influence the microgeometry of precision cast.

Computer analysis of images and related with it fractal analysis of the structures allows for precise determination of changes in the evaluated structures. In the described studies distribution of porosity was determined. It was also shown that there is a clear differentiation of porosity occurrence in the directions perpendicular to each other.

The micro-geometry results confirm the diversity of ceramic mould surface morphology. The micro irregularity level defined for the bottom wall (D) perpendicular to the axis of sprue (WG) is lower than the side walls (B) parallel to the axis of the sprue.

Perpendicular to the walls of the casting system (wall D and G) the layer is thicker than the liquid ceramic mould material in the parallel direction (wall B). Structure of the wall (B) is characterized by a reduced share of the liquid ceramic mould material and minimum distances between grains of loose ceramic mould material, with tending to their "increased density". Which result in that between the successively imposed layers of liquid ceramic mould material the liquid portions are relatively large. This cause a large diversity in mould density. The result is that the R_a value of the wall (D) and (G) are higher, with large deviations.

In the case of the issues related to the modeling of solidification of metal in the mould it is important to correctly determine the coefficient of heat transfer λ for the ceramic mould, and not only its materials. In this regard, it is important to develop a methodology to determine λ and appropriate research station.

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