POROSITY ANALYSIS OF MULTILAYER CERAMIC MOULDS USED IN INVESTMENT CASTING OF AIRCRAFT ENGINE PARTS

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Abstract

Computed Tomography (CT) as a known medical research method is nowadays widely used in research institutions and production companies. Due to its nondestructive testing nature, CT finds application in both final product quality control such as castings or CNC machined parts and research of new materials, e.g. ceramics, composites etc. In aviation industry, one of the main factors in investment casting, crucial to quality of final product are properties and condition of ceramic moulds. Inspection is possible only after filling mould with molten alloy and breaking it after metal solidification. The purpose of article is to examine application of computed tomography in ceramic casting moulds quality control and investigation of certain ceramic pulp components effects on mold porosity and voids characteristics. Specimens in shapes of casting moulds were prepared. Samples were produced using quartz, molochite and various binders. They were examined with micro CT tomography. Test results were presented as high quality 3D models and 2D CT slices of specimens and percentage porosity. As a comparative method of obtaining porosity data, mercury porosimetry tests were carried out.

Keywords: Porosity, ceramic mould, computed tomography

1. INTRODUCTION

MicroCT scanners, the widest group of CT devices used in research of products quality and materials analysis originate form their medical related X-ray CT equipment form from the mid-70s. From the 90s until mid-2000s, CT appearing in industry were used mostly to visualizing defects and interior of the products due to the lack of precision, comparable with conventional instruments for geometric measurements [1, 2]. In recent years besides improving the accuracy of measuring devices, the number of tests and analysis of ceramic materials pores and voids are taking place across the world. A wide group of CT tests of ceramics are those dedicated to concrete and asphalt, consisting, like the lost-wax casting molds, mostly ceramic fillers and binders. Jarjen's team [3] analyzed the effect of distribution and shape of voids inside road asphalt on absorption and evaporation of water in time. Lu's team [4] introduced i.a. method of separation on tomographic images porosity of cement mass binder and porous aggregate used as a filler. Schock's team [5] performed tests of the inspection capabilities of the CT device with two radiation sources to visualize complicated void systems inside construction concrete samples. In order to increase the usability of CT devices in geometrical measurements of pores and voids, Hermanek and Carmignato [6] also proposed a special calibrating object and demonstrated the effect of X-ray parameters on the accuracy and repeatability of measurements. Haratym and Biercanki [7, 8] provided multidimensional studies of the physical properties of ceramic molds, including estimating the porosity of a mold fragment based on the ratio of pores pixels to the total number of pixels in the selected cross-section image. In contrast, Matysiak's team [9] determined the percentage porosity on the cross-section images by separating the ceramic pulp slice on the image and calculating the parameter only for it. The literature analysis shows that knowledge about the distribution of the porosity of layered ceramic molds and the impact of a number of materials on its morphology is little developed, which contributed to the creation of this article. The purpose of the research is to analyze the impact of various ceramic materials intended for the production of multi-layer molds on their porosity and pore distribution. For the porosity studies, a micro-CT device v|tome|x L 450 device was used, whereas for comparative purposes mercury porosimetry tests were carried out using the Poremaster 60 device.

2. METHODOLOGY

The subject of the research (**Figure 1**) were three identical seven-layer lost-wax casting ceramic moulds referred later in the publication as Form 1, Form 2 and Form 3 with five details in the shape of air blades. Each of the samples was made on the basis of a different mix of ceramic materials: two types of sand fillers and water or alcohol binders (**Table 1**).

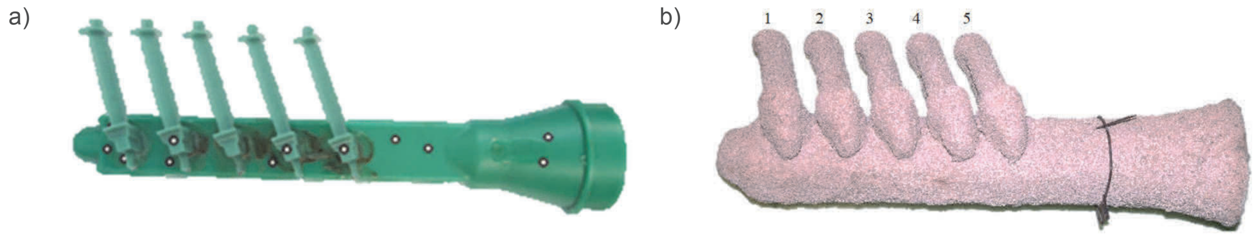

Figure 1 Research material: a) wax model used to produce test moulds, b) sample ceramic mould

Table 1 Ceramic mould samples components

Sample	Layer	Binder	Filler
Form 1	1	Hydrolyzed ethyl silicate (viscousness ok. 32 s)	Quartz sand 0.1-0.3 mm
	2	Hydrolyzed ethyl silicate + quartz powder (viscousness ok. 20 s)	Quartz sand 0.1-0.3 mm
	3	Ludox PX 30 + quartz powder (viscousness ok. 24 s)	Quartz sand 0.5-1 mm
	4-7	Ludox PX 30 and hydrolyzed ethyl silicate (alternately)	Quartz sand 0.5-1 mm
Form 2	1	Ludox PX 30 + molochite powder (viscousness ok. 24 s)	Molochite sand 0.1-0.3 mm
	2	Hydrolyzed ethyl silicate + molochite powder (viscousness ok. 24 s)	Molochite sand 0.1-0.3 mm
	3	Ludox PX 30 + molochite powder (viscousness ok. 24 s)	Molochite sand 0.5-1 mm
	4-7	Ludox PX 30 and hydrolyzed ethyl silicate (alternately)	Molochite sand 0.5-1 mm
Form 3	1	Remasol Plus + quartz powder (viscousness ok. 30 s)	Quartz sand 0.1-0.3 mm
	2	Remasol Plus + quartz powder (viscousness ok. 24 s)	Quartz sand 0.1-0.3 mm
	3-7	Remasol Premium + quartz powder (viscousness ok. 24 s)	Quartz sand 0.5-1 mm

Each form was subjected to various porosity tests. Micro CT v | tome | L L 450 was used for the research, which through a series of x-rays of examined object provided cross-sectional tomographic images and after reconstruction in dedicated VGStudio software also spatial models of samples. Analysis of tomographic cross-sectional images located with help of spatial CT models via VGStudio and myVGL software were carried out. ImageJ software was used to binarization, thresholding and separation of porosity from the ceramic mass in cross-sectional images. Estimation of the percentage porosity of the samples were made, comparing the ratio of pore pixels to the sum of the remaining pixels of the cross-sectional images. Mercury porosimetry tests involving the mercury injection inside the sample and the measurement of pressure related to this process, for comparison purposes, were made with the Poremaster 60 device on a single random choosed fragment of a mould detail of each sample containing the material of the first and further construction layers. Tests multidimensional pore data in form of graphs and tables.

3. RESULTS

The longitudinal cross-sections of the moulds shown in **Figure 2** present the potential effect of the detail geometry - the jet engine blade, on the distribution of porosity. The presence of large voids and the concentration of pores in the first construction layers of the transition from the blade root to the turbine blade is noticeable. In the case of Form 2, this characteristic is present in 8 out of 10 cases, while in Form 3 6 out of 10. Form 3 has the least of them due to its visually most compact structure of the ceramic mass. The characteristic feature of the sample was the rare occurrence of large voids, not concentrated in a specific part of detail sections, and the noticeable layering of the mould wall (darker shade of gray) with a locally layered porosity of very small diameter, undetectable when determining the percentage porosity parameter by CT. No significant impact of the difference in the ceramic mass components of individual construction layers on the distribution of porosity was found. Form 2 was characterized by the occurrence of voids chains between the last structural layers, especially the last one. Apart from randomly occurring voids in the first layers and, similarly to Form 3, visible lamination of the mold wall, it can be concluded that the mixture of the last structural layers favors the concentration of porosity between the layers. Form 1 had characteristic local chains of porosity of large dimensions in the middle part of the mould wall. It is not possible to correlate such distribution of pores with the differences in the ceramic mixture on subsequent construction layers, however, it can be stated that the first structural layers accumulate a significant part of large, irregular voids.

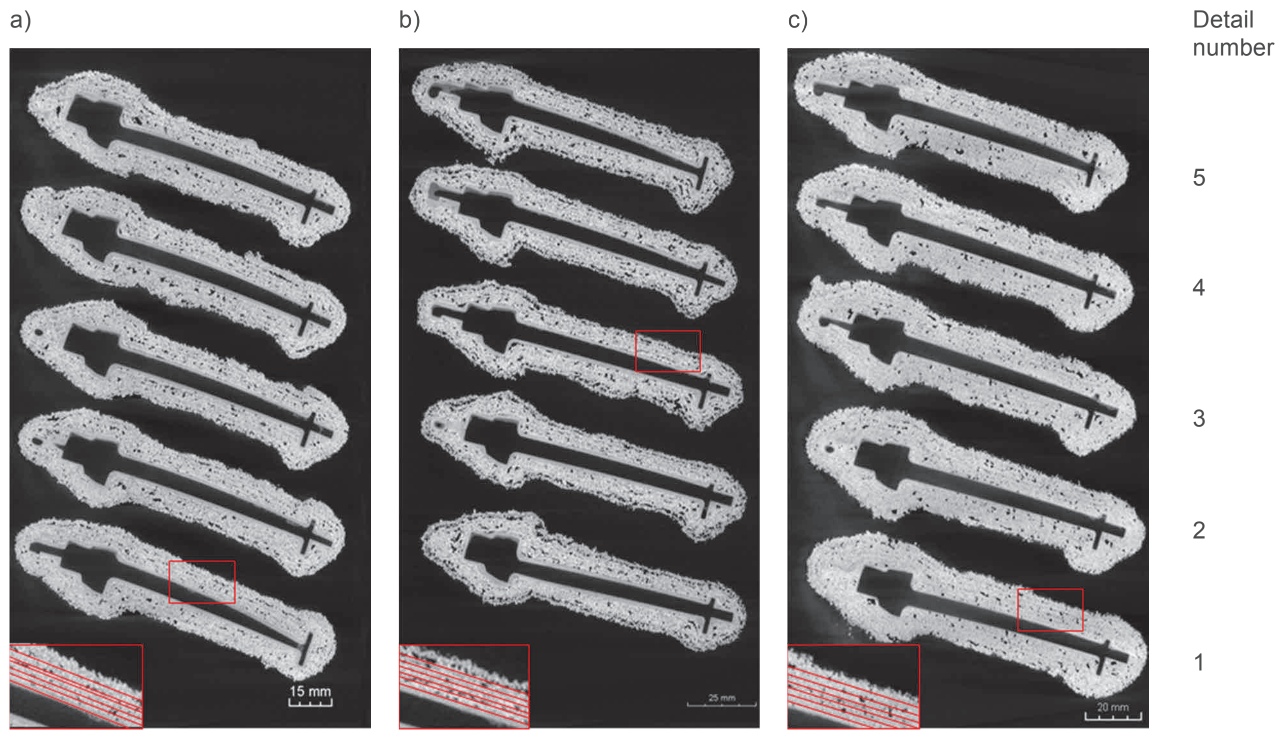

Figure 2 Longitudinal cross-section of moulds details**:** a) Form 1, b) Form 2, c) Form 3

The cross-sections of the details shown in **Figure 3** reveal the effect of the deflection of the blade and confirm the analysis of the effect of the geometry of the detail and the materials contained in individual layers of the ceramic wall for the distribution of porosity. All three samples were characterized by the occurrence of large size voids and the concentration of porosity between first construction layers in sharp bends of the walls of the mould near blade root (cross-section 1) and the arc of the blade itself (cross-section 2). Characteristic features revealed in cross-sections were the frequent occurrence of large voids at the border of the first layer and further construction layer in cross-section 1 at the level of blade root platform of Form 2 and linearly concentrated large voids in the same cross-section of Form 3. Both of these defects can be linked to the geometry of the wax model, influencing the way of ceramic pulp application to the mentioned critical places during the moulds making.

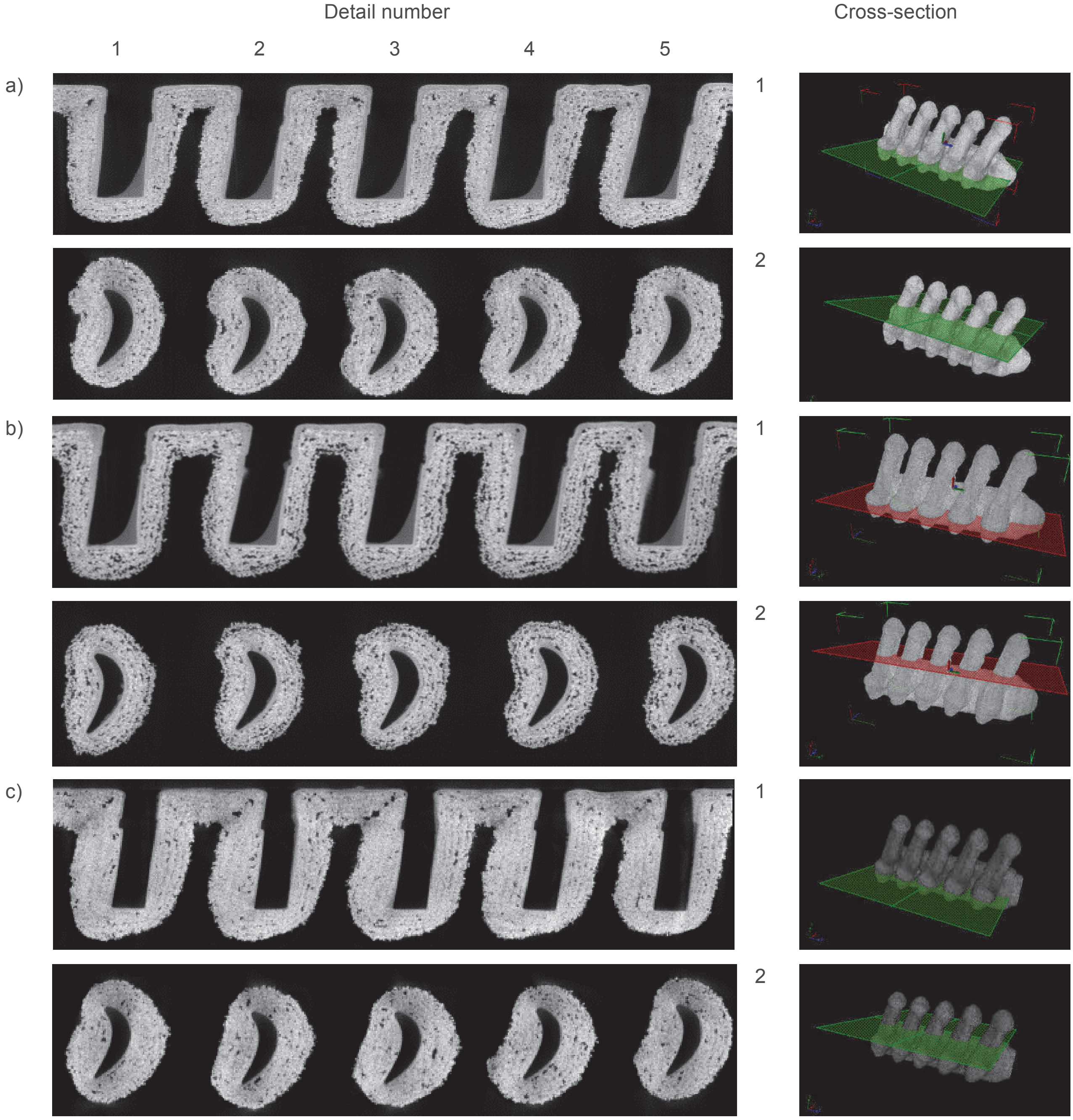

Figure 3 Transversal cross-section of moulds details: a) Form 1, b) Form 2, c) Form 3

Mercury porosimetric differential and summation diagrams (**Figures 4a** and **4b**) show the existence of three ranges of pore diameters, slightly differing form each other depending on the ceramic pulp mixture. The main populations were pores with a diameter between 0.5-3 μm and 50-70 μm. Based on CT images, it can be concluded that these are the pores of the first layer and a part of the pores of the further construction layers, where the pores larger than 10 μm occurring in the first layer are treated as evident form defects. The second range of pores with a diameter of approx. 100 μm to approx. 500 μm is irregularly occurring large voids that may have negative effect on durability and the thermal properties of the mould. The third pore diameter range, below approx. 0.5 μm, is not detectable by CT. However, it can be presumed that these pores are located in a ceramic binder and a first mould layer. This porosity range is the main reason for the differences in percentage porosity of samples (**Figure 4d**) and their surface area (**Figure 4c**) - especially for Form 2. Its low pore diameter compared to other samples results from the large surface area associated with the occurrence of large amounts of porosity with diameters not exceeding 1 µm. It should be emphasized that the mercury porosimetry tests has not global character like CT, while the methodology of estimating the percentage porosity, i.e. the binarization and thresholding process, as well as the separation of the tomographic device itself, contributed to the underestimation of the parameter. For this reason, the order of the parameter size is as follows: Form 1 <Form 2 <Form 3, and this is confirmed by the results presented on mercury porosimetry graphs. In the case of the mercury porosimetry test of the Form 3 sample, it has a higher porosity than Form 2 due to the visible peak on the pore diameter range of 0.7-1.3 µm and the peak shift in the diameter range of 1-12 µm towards the larger pore diameters. The material of the Form 2 sample, despite the largest number of pores with a diameter of up to 1 µm and in the range of 5 - 10 µm, has a porosity slightly more than 2% smaller. The Form 1 differential curve shows the lowest volume values for most pore diameters compared to the remaining samples. Only the fraction of the largest pores is high in this sample, which affects moulds porosity at the level of 10.82 %.

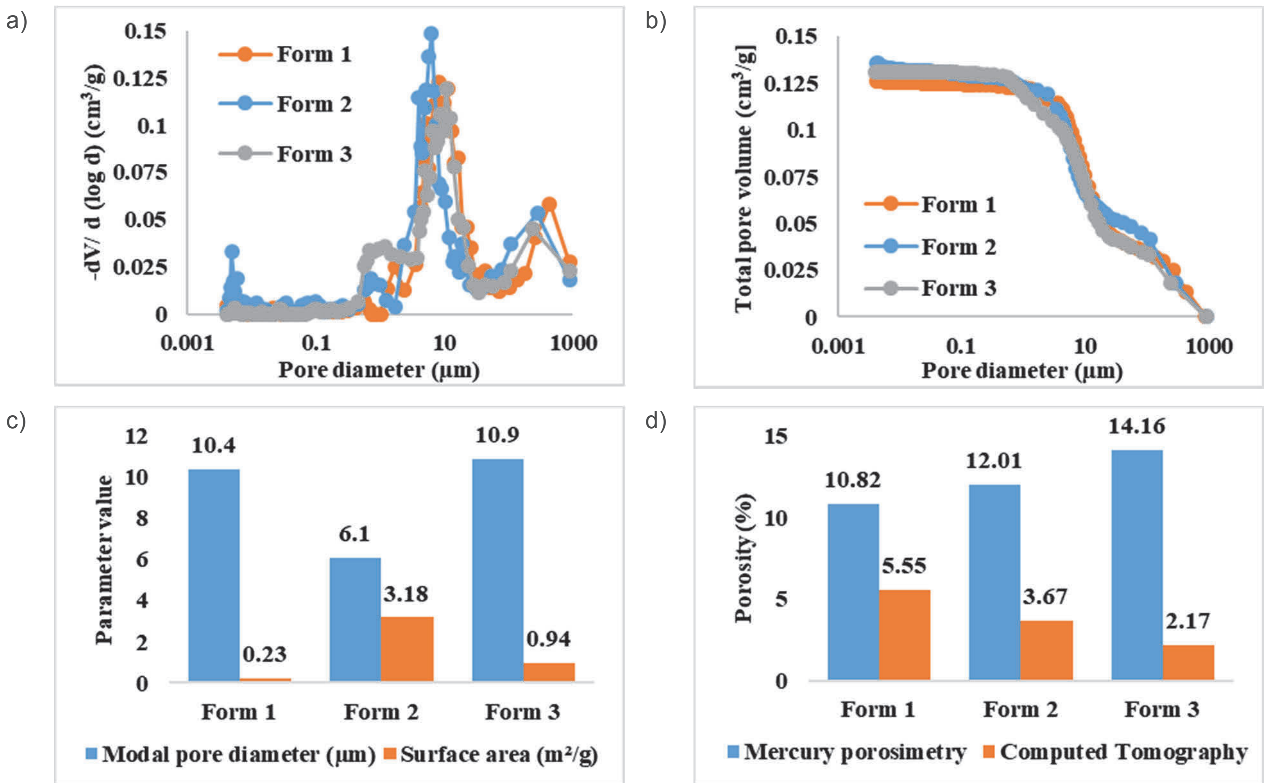

Figure 4 Porosity characteristics: a) mercury porosimetry differential curve, b) mercury porosimetry summation curve, c) mode pore diameter and surface area, d) percentage porosity calculated by mercury porosimetry and CT method

4. CONCLUSION

The publication presents studies on the influence of diversified composition of materials used in lost-wax ceramic casting moulds production on their porosity. The influence of components of the ceramic pulp and its application on subsequent mould layers on the characteristics of porosity, including its percentage ratio to the ceramic mass, was determined. The relationship between numerical porosity data, determined by specialized research methods and the estimated size of the porosity of the samples were presented. Tests were not shown any effect of the location of the detail on the infusion system on the specific distribution of porosity and the influence of significant differences in the porosity between the layers of different viscosity. Based on the results, it can be concluded that the geometry and the type of material affect the distribution and the amount of pores in a way that it may potentially diversified gas-permeability, strength of the structure, as well as the removal of heat from the mould. Due to the large number of individual pores occurring in a very small volume, the analysis of CT visual data is only possible in the case of cross-sectional images and is a good way to test ceramics in terms of overall quality.

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