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Studies of Accelerated Drying of Ceramic Moulds with the use of Microwaves

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Abstract

The article presents the results of studies of the process of accelerated drying performed by means of microwave radiation of ceramic moulds deposited on patterns made of foamed plastics used in the Ceramic Shell technology. The studies aimed at determining the microwave radiation parameters (power, downtime, and uninterrupted operation time) in order to obtain the maximally short drying times which do not cause pattern destruction. The analysis of results confirmed that an increase of the microwave radiation power shortens the drying time of the particular layers of the ceramic mould, however, at the same time, it excessively raises the temperature of the mould. With the microwave power over 1200 W, we can obtain the drying time of one layer at the level of about 30 min, and the temperature of the mould reaches the value of 70^{o}C, which does not cause deformation or partial melting of the polystyrene pattern.
From the point of view of production effectiveness, as a result of the application of microwave drying, the time of production of ceramic moulds was shortened from 7 days to 1 working day.

Keywords: Casting, Ceramic mould, Microwave drying, Foamed patterns, Replicast CS

1. Introduction

The investment casting process is one of the basic methods of producing precise complicated small mass casts [1-3]. This is related to the fact that a mould joint is not required, and the internal cast surfaces can be obtained without the use of cores. In this technology, various types of waxes are used for the patterns (synthetic and natural). Owing to the application of wax (melting point over 40^{o}C), the mould drying temperature usually does not exceed 23^{o}C. This is connected with a prolonged time of drying and, under industrial conditions, the drying of each coating taking place at ambient temperature for the duration of one day. And so, making a typical 7-layer mould lasts about a week. In view of this fact, researchers are looking for various methods to shorten the manufacture of ceramic moulds [4].

A technology similar to the lost wax method is Replicast CS [5, 6]. Replicast CS (ceramic shell) is a process in which wax patterns have been replaced by patterns made of foamed large-particle materials in metal moulds with high dimension and shape precision. The patterns are mounted into sets, on which layers are deposited by being submerged in liquid ceramic mixtures. After each submersion, the deposited coating is subjected to a dehydration process – drying. With the use of plastic patterns, the drying temperature can be increased to about 70^{o}C, which makes it possible to significantly shorten the time of drying the particular layers. Through multiple deposition of layers of a ceramic mixture, we obtain a ceramic mould. Next, at the temperature of 925÷1000^{o}C, the moulds are annealed. During the annealing, burning of the foamed pattern and hardening of the ceramic mould are performed.

The Replicast CS method is gaining more and more interest in the world as an alternative to the lost wax technology, especially for casts of a bigger mass. This results from the fact that patterns made of foamed large-particle materials are lighter than smelted patterns, with a comparable dimensions and shape precision.

In the presented investigations, in order to dry moulds based on water ceramic coatings, microwave drying was applied – a method which is more and more commonly used in various industrial branches in the world [7-13]. The technology of drying laminar ceramic moulds by means of microwave radiation has been developed and patented by Qbig Limited Partnership. The application of microwave radiation to dry ceramic moulds results from its many advantages:

- for the ceramic mass, water coatings based on colloidal silica were used (water absorbs the microwaves and heats up very well),
- a plastic (polystyrene) pattern is a dielectric, which does not absorb microwaves,
- low operation costs – it is characteristic of microwave heating to absorb the microwaves only in the thermally processed product, without the necessity of heating the whole device,
- small sizes of the microwave installations.

2. Test methodology

The accelerated drying tests were carried out in a prototype microwave drier produced by Qbig Co., whose chamber has been shown in Figure 1. The microwave drier has 3 microwave generators (frequency of 2450 MHz) with the power of 900W each. The total power of the microwave drier equaled P_t = 2700 W. The chamber of the microwave drier has the following dimensions: 1.04 m x 0.86 m x 1.06 m, hence the volume of the chamber equaling 0.95 m^3. It has a rotational holder centrally on its ceiling with a tool mounting system SDS, to which it is possible to attach a table, or a big pattern equipped with a proper holder with an SDS connection.

Fig. 1. View of the chamber of a microwave drier produced by Qbig

The prototype microwave drier made it possible to control the working time and the downtime of the microwave generator. In order to determine the drying parameters, a series of measurements were made of the mass of the experimental sets as well as their temperature for different microwave generator's working cycles and downtimes, which have been presented in Table 1. By way of steering the working cycle through changing the operation time and downtime of the microwave generator, the processing power was determined P_c.

The processing power was calculated from equation (1):

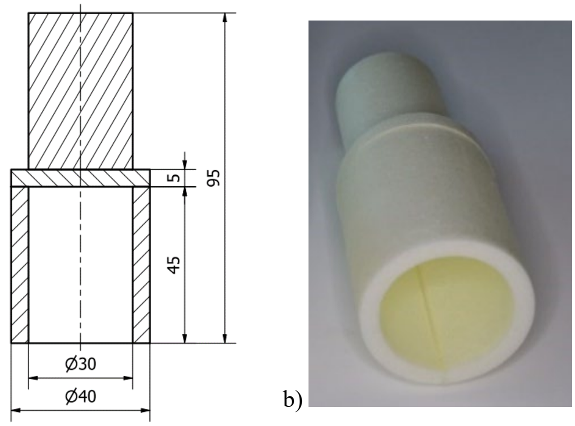
$$P_c = \frac{t_w}{t_w + t_p} \cdot P_t, \text{ W} \quad (1)$$

where:
P_c – processing power, W, t_w – operation time, s, t_b – downtime, s, P_t – total power, W.

Table 1.
Working cycles of the microwave drier

Cycle no.	t_w, s	t_b, s	P_c, W
1	**4**	8	900
2	**4**	6	1080
3	**4**	5	1200
4	**5**	8	1038
5	**5**	7	1125
6	**5**	6	1227
7	5	**5**	1350
8	6	**5**	1473
9	7	**5**	1575
10	8	**5**	1662
11	10	**5**	1800

The patterns were prepared from extruded polystyrene in the form of closed bushings with the diameter of 30 mm, length of 45 mm and wall thickness of 5 mm. The experimental pattern has been shown in Figure 2.



a)

Fig. 2. A pattern of a closed bushing made of extruded polystyrene, a) a cross-section, b) a view of the applied pattern

Within the investigations, the material for the ceramic moulds was chosen, the selection criterion being their assigned application, i.e. casting of nonferrous alloys or light alloys. Water coatings based on colloidal silica with Refracoarse flour were used. Refracoarse sand was applied as the sand pack, which made it possible to cast moulds with a low temperature, below <100°C [14-18].

For each experimental drying cycle conducted according to Table 1, 5 pattern sets were prepared. The initial configuration of the experimental sets used for the drying process tests has been compiled in Table 2.

Table 2.
Initial configuration of the experimental sets

Set no.	Experimental set configuration	Description of layers made on the experimental set
E1	One layer	1 layer - Refracoarse 0.1÷0.3 mm
E2	Two layers	1 layer - Refracoarse 0.1÷0.3 mm 2 layer - Refracoarse 0.5÷1.0 mm
E3	Three layers	1 layer - Refracoarse 0.1÷0.3 mm 2 and 3 layer - Refracoarse 0.5÷1.0 mm
E4	Four layers	1 layer - Refracoarse 0.1÷0.3 mm 2, 3, 4 layers - Refracoarse 0.5÷1.0 mm
E5	Six layers (reference pattern - dried)	1 layer - Refracoarse 0.1÷0.3 mm 2, 3, 4, 5, 6 layers - Refracoarse 0.5÷1.0 mm

Set 1 was without a coating, Set 2 had one dried layer of fine Refracoarse sand with the granularity of 0,1÷0,3 mm, Set 3 had two dried layers (the second layer was covered with coarse Refracoarse sand with the granularity of 0,5÷1,0) and Set 4 had three dried layers. Set 5 was used as the reference pattern, with all 6 dried layers. On the patterns in sets: 2, 3, 4, 5, fresh layers of a ceramic mixture were deposited and then the patterns were covered with fine sand in the case of the first layer and with coarse sand in the case of the successive layers, which is in agreement with the conventional technology of producing ceramic moulds in the lost wax technology [19].

The diagram of the conducted experiments has been shown in figure 3.

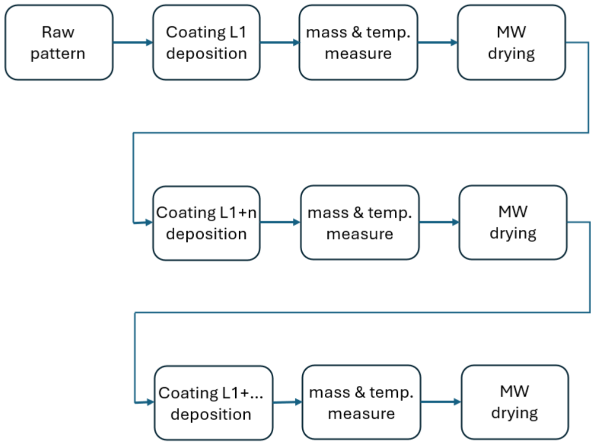


Fig. 3. The diagram of the conducted experiments

The four experimental sets with the freshly applied layer and the one totally dried six-layer set (Fig. 4) were placed in the prototype drier.

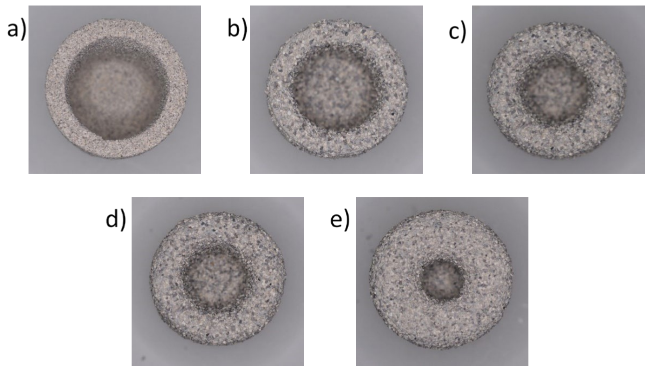


Fig. 4. Experimental sets after the layer deposition and drying: a) Set 1, b) Set 2, c) Set 3, d) Set 4, e) Set 5 (reference)

The experimental sets were dried for 40 minutes. The mass measurements of the experimental sets (foamed polystyrene pattern with a deposited layer) and their maximal temperature inside the bushing were made every 10 minutes. The mass measurement was carried out by means of a RADWAG PS8000/C/1 balance with the accuracy of 0.01 g.

In order to accelerate the temperature measurement, an infrared camera KEYSIGHT TECHNOLOGIES U5857A was used, which made it possible to record the measurement results in the form of colourful graphics. Specification of the applied camera: thermal imager, 28deg H x 21deg V, 10cm; temperature min: -20°C; max: 1200°C; IR resolution: 320 x 240; thermal sensitivity, (NETD): 0.1°C.

3. Test results

Due to the small masses of the layers and the water contents at the level of 15%, the water mass in the coating layer varied between

1.5 and 4.5 g. Because of the above, the mass losses during the drying would have been very visible. For this reason, in order to better illustrate the changes in the water content in the layer, a decision was made to present only the water loss, by subtracting the dried layer mass from the layer mass and determining the degree of its drying. The drying degree was determined according to equation 2.

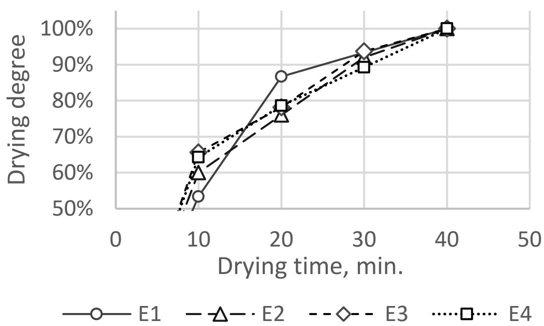
$$D = \frac{M_V}{M_{LP}+M_{LK}} \cdot 100, \% \tag{2}$$

where:
D – degree of drying, M_v – mass of the evaporated water from the moment when the layer is applied to the moment when the measurements are made, g; M_{LP} – initial mass of the set measured after the layer's application, g; M_{LK} – mass of a dry set – determined as the lowest mass for the set, g, which does not decrease during further drying.

3.1. Drying for a cycle with a constant microwave working time 4 s

Figure 5 shows representative results of the change in the drying degree of the layers of a ceramic mould for cycle 1 and 3. With a longer downtime (8s), the drying degree for 20 min equals about 80%, whereas with a downtime of 5 s, it increases to about 90%.

a)



b)

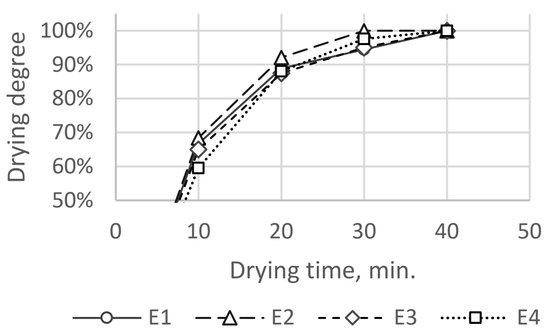
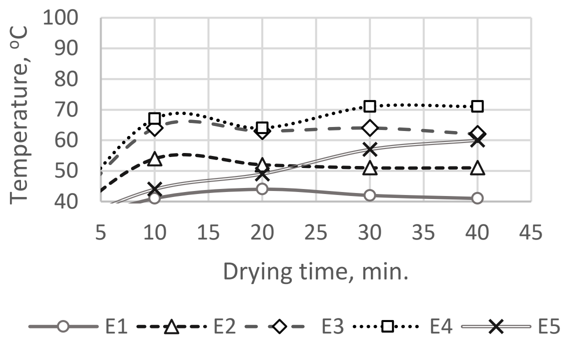


Fig. 5. Drying degree for a) cycle 1, b) cycle 3

Figure 6 presents the temperature changes of the particular layers depending on the time, for cycles 1 and 3. When the downtime of the generators is shortened, we observe an increase of the layers' temperature. For layer 4, the temperature is higher because, as a result of an increase of the mould's wall thickness, the opening and the heat removal surface area decrease. It should also be noted that the highest increase of temperature takes place for the first 10 minutes, when intensive evaporation of the water from the layer occurs.

A dry ceramic mould (Set 5), although it does not contain water, heats up as well, and the temperature increase is more uniform than in the case of the freshly deposited layers. This means that the previous layers, already dried, heat up the new layers on the inside and accelerate the drying process.

a)



b)

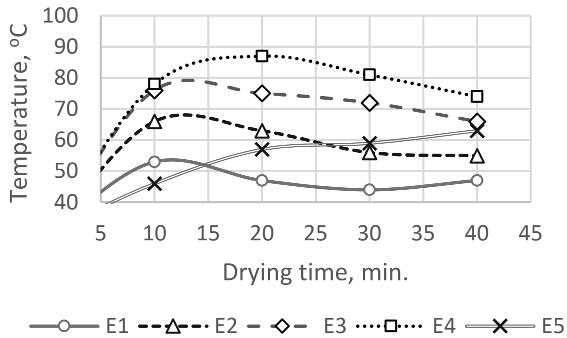


Fig. 6. Temperature changes of the layers for
a) cycle 1, b) cycle 3

Figure 7 shows the recorded images of the temperature measurements of the examined experimental sets by means of a infrared camera for cycle 1. We can notice that the uniformity of the layers' heating increases together with the drying time and the number of layers.

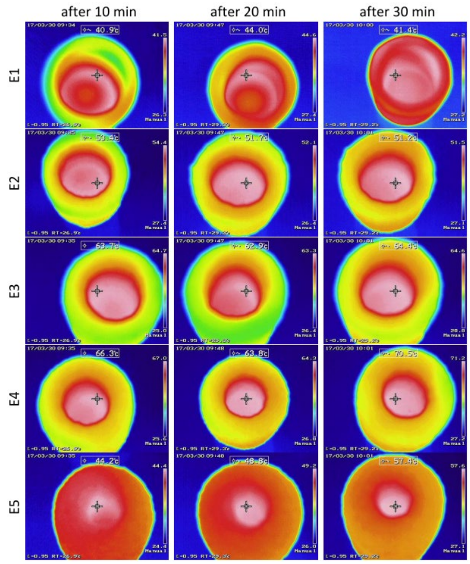
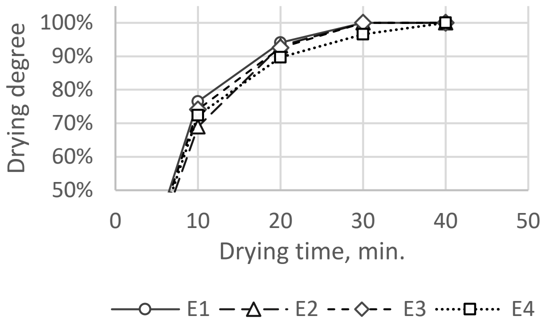


Fig. 7. Temperature distribution of the experimental sets for cycle 1

3.2. Drying for a cycle with a constant microwave operation time 5 s

The changes in the drying degree of the ceramic mould's layers for different drying cycles have been presented a figure: for cycle 5 – Figure 8a, for cycle 7 – Figure 8b.

a)



b)

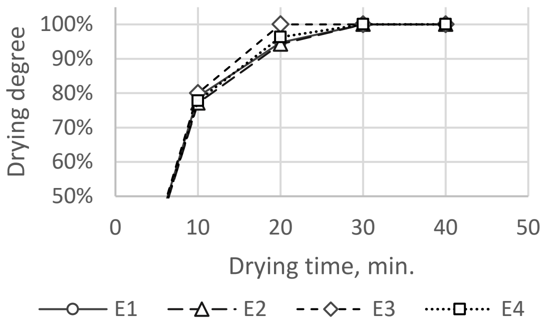
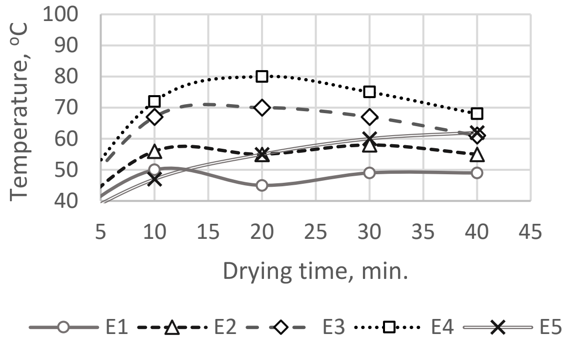


Fig. 8. Drying degree for a) cycle 5, b) cycle 7

It can be inferred from the figure that reducing the downtime only by 2 seconds, we can obtain the same degree of drying of layers 2-4 in a time shorter by 5 minutes. In turn, layer 1 can be treated as dry after 20 min. The drying time is 10 min shorter than in the case of the cycle with a 7 second downtime.

Figure 9, in turn, presents the changes in the temperature of the particular layers depending on the time for exemplary cycles: 5 and 7. With an increased microwave power, in this case, we observe an increase of the layers' temperature from 5 to 10°C.

a)



b)

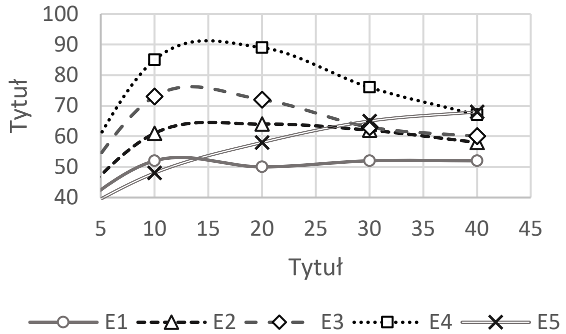


Fig. 9. Temperature changes of the layers for a) cycle 5, b) cycle 7

Figure 10 compiles the temperatures of all the layers depending on the cycles, 4÷7, after 20 min of drying. It can be inferred from the data that each reduction of downtime by 1 s reduces the layer's temperature by about 5°C in a uniform way, whereas an increase of the layers' number by one causes an increase of its temperature by 10°C. We should, however, remember that these are the maximal temperatures of the mould measured inside the opening, from which the heat removal is difficult.

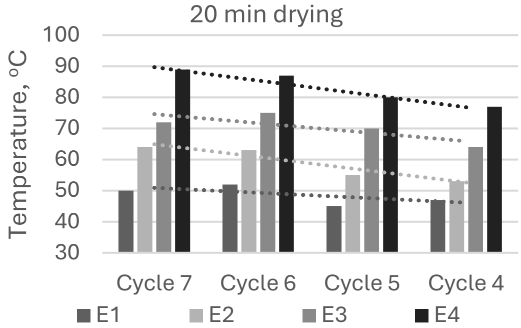


Fig. 10. Temperature changes of the layers depending on the cycles and the number of layers

The characters of the temperature distribution (for drying cycles 4÷7) on the tested experimental sets determined by means of an infrared camera are similar to that of cycle 1. The highest temperature values were observed inside the bushing's opening, which are about 20°C higher than on the external surfaces.

3.3. Drying for a cycle with a changeable microwave operation time and a constant downtime (5 s)

In this part of investigations, for constant downtimes equaling 5 s, the microwave operation time was gradually increased within the scope of 6-10 s. The results of the tests of the ceramic mould layers' drying degree for cycles 8 and 11 have been presented in Figure 11. Unfortunately, an increase of the microwave power does not bring an effect in the form of a shortened drying time, which still remains at the level of 20 min.

The increase of the microwave power significantly raised the temperature of the ceramic moulds, which can be noticed in Figure 12, which includes a diagram of the temperature changes of the particular layers depending on the time for cycles 8 and 11. For the longest examined operation times (10 s), both layers 3 and 4 reach high temperatures of about 90°C. Also, the 6-layer dry mould heats up excessively. After the 20 min cycle, when the layers are dried, its temperature is over 70°C.

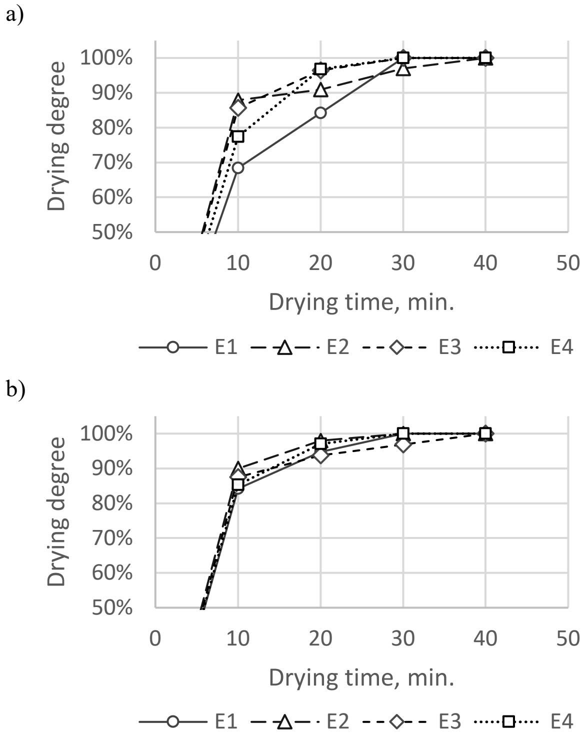


Fig. 11. Drying degree for a) cycle 8, b) cycle 11

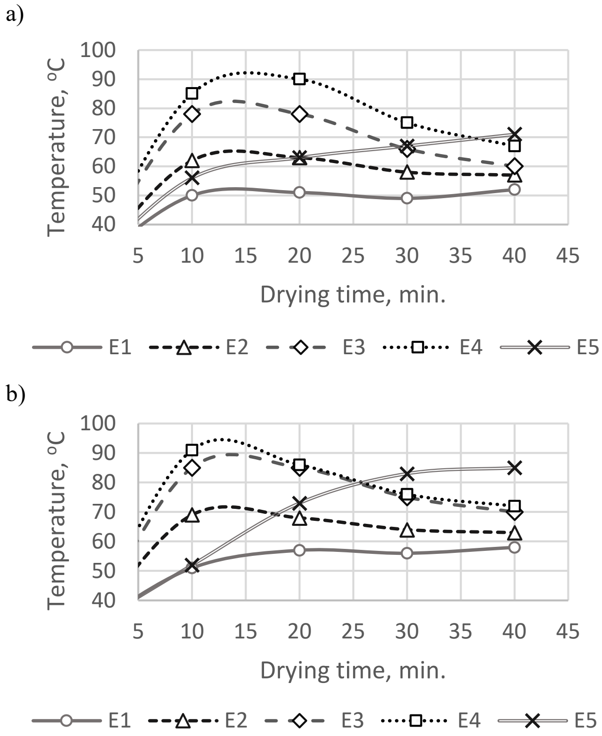


Fig. 12. Temperature changes in the layers for a) cycle 8, b) cycle 11

4. Summary

It can be inferred from the presented investigations that the drying time of the first layer is the shortest. The successive layers become dry at a similar speed to each other. The layers of a ceramic mould can be treated as dry after 30 minutes. With the highest microwave powers, the drying time can be shortened even to 20 minutes.

However, during the selection of the proper cycle, we should also take into consideration the heating temperature of the particular layers during the drying cycle. It can be concluded from the conducted tests that a ceramic mould does not heat up to a degree which would pose a risk of damage to the pattern on which it is deposited. However, too high a temperature of the ceramic mould after the drying cycle causes the necessity of its cooling (which prolongs the process) in order to apply the successive layer of the ceramic mass. Submerging an excessively heated mould in the ceramic mass causes rapid drying of the mass film and problems with sticking of the sand to the film during the covering time. And so, cycles with the microwave powers below 1200 W should be applied.

The maximal temperatures of layer 1, even for the cycle with the highest power, do not exceed 60ºC. For the successive layers, we can notice a certain dependence. They reach the highest temperatures in the first 10 and 20 minutes of drying and then the temperature of the layers decreases. The initial temperature increase is caused by the water evaporation, when, for the period of 20 minutes, 90% of water is removed from the layer. Then the temperature drops and approaches the temperature of the dried layer.

The temperature of the dried 6-layer mould gradually increases with the drying time and the microwave power. This means that the internal layers of the mould, which are already dry, aid the drying process of the newly applied external layers.

Moreover, we can infer from the conducted tests that the use of microwave drying of ceramic moulds in the investment casting method or the Replicast CS process reduced the time of producing the mould from 7 days to 1 day, which is very important from the point of view of production effectiveness.

Acknowledgements

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Project title: Development of an innovative device using a unique technology of fast production of laminar ceramic moulds for precision casting.

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