Optimization of ceramic manufacturing process using Plackett-Burman design of experiment

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Abstract

In this research, the authors describe the ceramic injection molding process, and its most important features. Using the method of design of experiment, the connection was discovered between the adjustable machine parameters and the quality of end product, especially highlighted the cracks in the ceramic body. The researchers found as main result, that the machine settings have more impact on the quality of end product, than the applied mold temperatures during injection molding. Furthermore, the holding pressure had the highest impact on the weight of end product, the weight increased with the holding pressure according to a linear relationship.

Keywords: alumina powder, ceramic injection molding, design of experiment, feedstock, paraffin wax

1. Introduction

The sophisticated ceramic, plastic and powder metallurgy industries and technologies require higher and higher demands against quality, volume and yield of end product [1, 2]. In the illuminant industry, for producing arc tube parts for high intensity discharge lamps the applied method is the ceramic injection molding. For producing ceramic arc tube parts (plugs), two different major components are used for producing injection molding raw material (hereinafter: feedstock): high purity alumina powder as the main component, and an organic paraffin wax as binder material. For producing the injection molding feedstock, the wax binder is melted in a sigma-blade mixer, and the alumina powder is sequentially mixed to the wax after it was melted. The properly mixed material is cooled down to room temperature, and - depending on the injection molding machine – it is granulated or crushed with jaw crusher. The fine tuning of the manufacturing process, the determination and controlling of the influential parameters have an outstanding importance on the production of high quality end product. Nevertheless, before any optimization of the feedstock preparation process, it is needed to know, determine and control the parameters of injection molding process. We can optimize the raw material only using a stabile, robust, properly adjusted injection molding machine, and therefore, the material properties and the producing process will be set for this optimized injection molding process, to decrease the amount of cracked ceramics [3-5]. Namely, in the present case, the output parameter eventually will be the injection molded, sintered parts, and their quality, and if the different materials are tested using a non-optimized injection molding process, then the injection molding will be only noise factor in the material experiments [6].

1.1. The properties of applied injection molding machine

The experimental ceramic parts (plugs) (*Fig. 1*) were made on full electronic injection molding machine with different settings.

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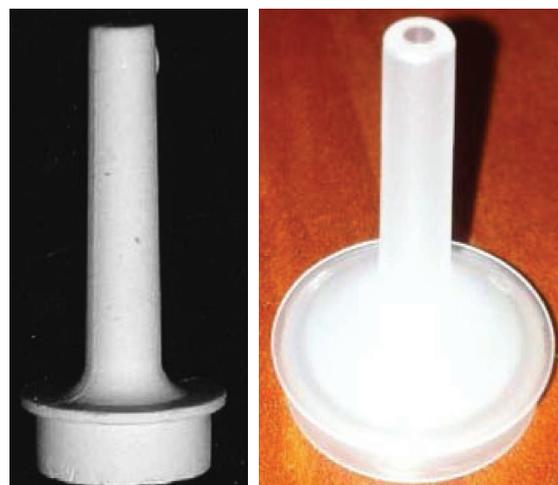
Fig. 1. Injection molded green part (a) and end product (b)
1. ábra Fröccsöntött nyers darab (a) és késztermék (b)

During molding, five external heating units can provide the proper temperature in the different parts of the mold: 2 heating units heat the hot side of the mold (manifold, tip), 2 units heat the cold side of the mold (side action and plug), and 1 unit heats the metering zone (barrel). Besides that, the machine is equipped with electronic nozzle heat (*Fig. 2*).

Since the machine is fully electronic, therefore it is well adjustable, and absolutely appropriate and usable for experimental purpose.

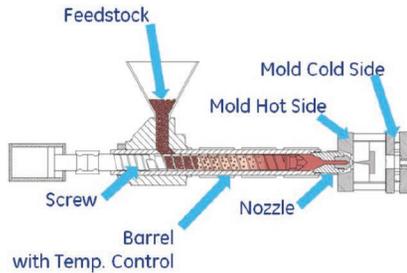The elements and run order of an injection molding cycle can be seen in *Fig. 3*.

Fig. 2. *The structure of injection molding machine*
2. ábra *A fröccsöntő berendezés szerkezeti felépítése*

1.2. Injection

During injection the screw linearly moves forward like a piston, and pushes material into the mold. During the process a closing ring under the screw tip ensures the material to flow into the mold, and not move backward in the barrel. During the injection phase 95-99% of the material of end product is added into the cavities [7-10].

The injection phase ends with reaching the switching point, which switch in the holding pressure section.

1.3. Holding pressure / Holding time

The injection phase is followed by the holding pressure phase. During the holding pressure phase the screw slightly moves forward with very low speed, since the mold cavity is almost full of material during the injection molding phase. The holding pressure gives the material, which fully load the mold cavity and complements the material loss from volume reduction due to the cooling of the part [11-14].

During the holding pressure phase, the control of the movement of the screw is provided by pressure values, and not by velocity, like in the injection section.
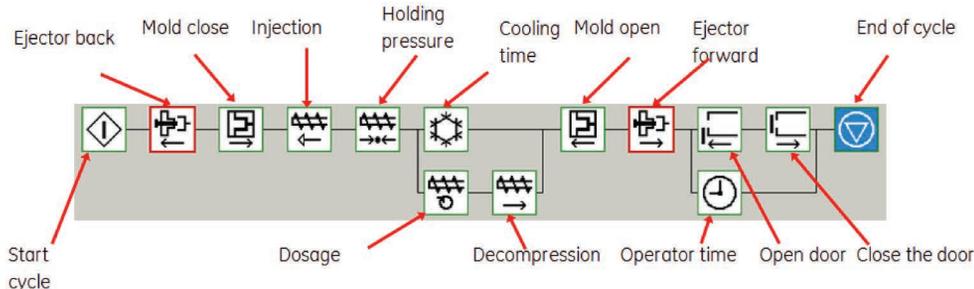
The holding time is the duration of holding pressure.

1.4. Dosage

After the holding pressure phase the screw starts to rotate and carries material forward. In front of the screw, the accumulated material pushes the screw backward. The duration of this phase is the time until the screw reaches the prescribed dosage length (material amount) in front of the screw.

The main parameters of the phase are the back pressure and the peripheral speed of the rotating screw (dosage speed).

The dosage speed should be kept low, since higher speed multiplies the wear rate of the screw. If the dosage speed is higher than necessary, the feedstock can be heated up, what is also harmful on the condition of the machine [15].

1.5. Back pressure

In the case of electric machines, the back pressure means the pressure, which holds against the accumulated material, which is in front of the screw, and which tries to push the screw backward during the dosage. If the back pressure is too low, the material in front of the screw can not be tight enough, and can be airy during the injection. If the back pressure is too high, the feedstock can be heated up, or due to the too high pressure, the screw can not load the material in the barrel [16].

1.6. Decompression

After the dosage phase the screw shortly and linearly moves backward; this is the decompression phase. The role of this phase is to decrease the pressure in the material after the back pressure. If the pressure is too high after the dosage phase, due to the back pressure, the material flows out from the hot side of the mold after the opening of the mold. The duration of this phase is the decompression path lenght [17].

2. Experimental

2.1. Plackett-Burman screening design with 10 factors (DoE)

The name „Screening Design" refers to a design of experiment, which can select some significant factors from a higher amount of factors, considered potentially adjustable factors.

Alternatively, if the main goal of a design is the identification of the main effects, regardless to the different interactions (which has probably lower magnitude), this design is called also Screening Design.

If one has initially numerous factors, firstly it is expedient to perform a sreening design, even if the final goal is the finding of a total output surface [18].

Typically, the screening design is a 3 level resolution design. This is very important, because the 3 level design can very effectively identify the main effects alias free, with low number of experiments.

2.2. The aim and implementation of experiment

As aim of experiment, it was intended to show the most important adjustable parameters of the injection molding machine, which have the highest effect on the yield and the occurrence of cracked parts.

Fig. 3. *Cycle diagram of injection molding*
3. ábra *Egy fröccsöntési ciklus folyamatábrája*

In the experiment, 10 different factors were investigated on 2 levels, with 15 runs. This means III. level resolution, i.e. the main effects are mixed with second level interactions [19]. There were 3 repeated cells as a part of the design to check the linearity and repeatability.

Every cell consisted of 333 parts. The performance of injection molding was continuous, with the same operator, raw material and molding tool. After the injection molding, the sintered parts were examined.

The investigated outputs (answers) of the experiment were the following:

▪ the amount (ratio) of cracked parts, yield [%]
▪ the weight of green parts [g]

In this research, the Minitab software helped to prepare the design of experiment and its evaluation process.

Based on the engineering point of view, earlier experience and literature [20] research the initially tested factors are shown in *Table 1*.

	Factor	Unit		Factor	Unit
1	Injections speed	mm/s	**6**	Dosage speed	m/min
2	Holding pressure	bar	**7**	Nozzle temperature	°C
3	Holdinh time	s	**8**	Barrel temperature	°C
4	Switching point	mm	**9**	Mold cold side temperature	°C
5	Back pressure	bar	**10**	Mold hot side temperature	°C

Table 1. Tested factors
1. táblázat A vizsgált faktorok

In Minitab software, in the yield-related analysis is better to use the transformed yield [21] instead of the good/all parts ratio, which is shown in eq. (1):

$$Yield_{Transz} = \frac{100}{90} \cdot ASIN\left(\sqrt{\frac{Good\ parts}{All\ parts}}\right) \qquad (1)$$

The transformed yield can approach the normal distribution, thus the results can be analysed more effective using the usual Minitab evaluation tools [22].

3. Results and discussion

Investigating the transformed yield of the parts, the following statements can be taken:

It can be observed on the Pareto chart of main effects (*Fig. 4*), that all main factors have significant effect on the transformed yield, except the nozzle temperature. The Pareto chart also gives an order by the level of the different effects. The most important 4 factors are the back pressure, holding pressure, injection speed and holding time.

The main effect plot (*Fig. 5*) shows, that which directions of factors have effect on the increasing of good end parts [23]. Based on *Fig. 5*, the low level of injection speed, the high level of the holding pressure, holding time and back pressure are favorable in the low crack amount point of view.

On the main effect plot (*Fig. 5*), the average yields of center points are indicated by the blue dots. Based on the data of center points, one can determine a strong non-linearity. By evaluation of results, it is important to highlight, that the perspicacity was made more difficult by the non-linearity and the low resolution

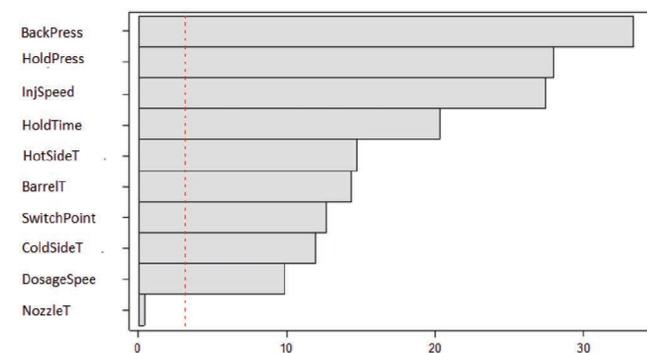of the experiment, due to the mixing of main and secondary interactions [24].

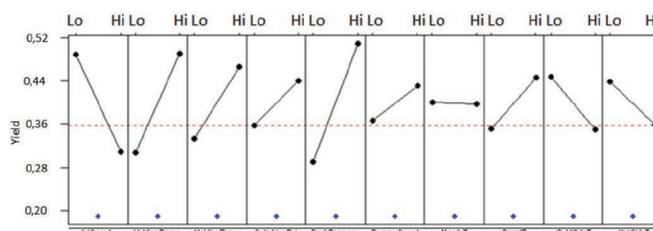Fig. 4. Pareto chart of main effects
4. ábra A főhatások Pareto-ábrája

Fig. 5. Main effect plot
5. ábra Főhatás ábra

Summary of the experimentally found settings for the different machine factors can be seen in *Table 2*.

	Screeninbest
Back pressure	High
Holding pressure	High
Injection speed	Low
Holding tome	High
Switching point	Medium
Dosage speed	High
Cold side temp.	Low
Hot side temp.	Medium
Barrel temp.	High
Nozzle temp.	Medium

Table 2. Experimental settings, the optimal level of factors
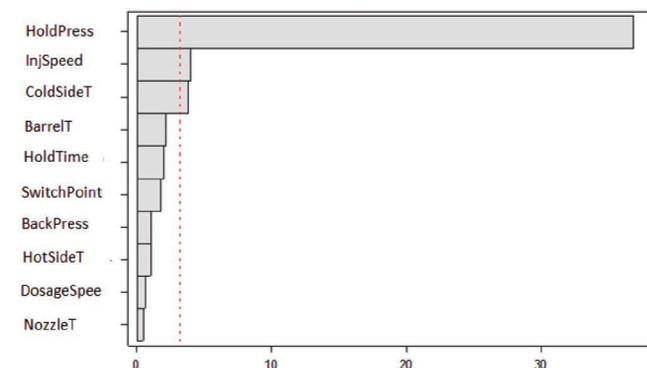2. táblázat A kísérleti beállítások és a faktorok optimális szintjei

Fig. 6. Pareto chart of main effects for green part weight
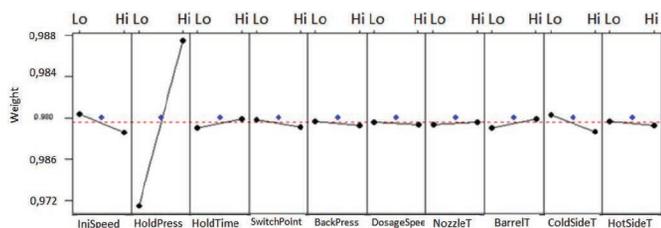6. ábra A nyers termék tömegére vonatkozó Pareto-ábra

Fig. 7.   Main effect plot of factors for the green part weight
7. ábra   A nyers termék tömegére vonatkozó főhatás-ábra

Observing the average weight related Pareto chart (*Fig. 6*) one can establish, that the value of holding pressure is the most significant factor for this output. On the main effect plot it can be seen, (*Fig. 7*) that higher holding pressure resulted higher green product weight, and the connection between these two parameters is approximately linear in the investigated range.

4. Conclusions

According to the results of literature research, the prepared experiments and the present observations, the following considerations can be taken:

The method of design of experiment is especially suitable for optimizing a given injection molding process, and the optimal setting for a given end product can be found. It was seen, that using the multi-factor Plackett-Burman Screening design, the less important factors could be safely filtered, and the optimal settings could be found.

According to the experiments it was established, that the machine settings have more impact on the quality of end product than the applied mold temperatures during injection molding.

The holding pressure had the highest impact on the weight of end product, the weight increased with the holding pressure according to a linear relationship.

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Kerámia gyártási folyamat optimalizálása a Packett-Burman kísérlettervezési módszer alkalmazásával
Jelen kutatásban a szerzők leírják a kerámia fröccsöntés folyamatát, annak legfontosabb jellemzőit. A kísérlettervezés módszerével bemutatják, hogy miként függ az egyes változtatható gépparaméterektől a végtermék minősége, különös tekintettel a kerámiában előforduló repedések megjelenésére. Legfőbb megállapításként elmondható, hogy a fröccsöntéskor beállítható gépparamétereknek sokkal nagyob hatásuk van a végtermék minőségére, mint a fröccsöntés hőmérsékletének. Ezen kívül elmondható, hogy a fröccsöntéskor a zöld termék tömegére az utónyomás nagysága van a legnagyob hatással.
Kulcsszavak: alumínium-oxid por, paraffin wax, kerámia fröccsöntés, kísérlettervezés, feedstock