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The use of the Taguchi approach to determine the influence of injection-moulding parameters on the properties of green parts

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Methodology of research

ABSTRACT

Purpose: The paper is focused on the influence of injection moulding parameters on the properties of green parts in powder injection moulding. Because of the nature of this technology all the technological phases must be mastered.

Design/methodology/approach: For the design of experiments (DOE) we used the Taguchi approach and the results were analysed with the analysis of variance (ANOVA).

Findings: As is presented in the paper the injection moulding parameters have big influence on weight and dimensions of the green parts. The mould temperature, material temperature and holding pressure are the parameters which influence the dimensions most. The influence of cycle time has to be examined in further experiments.

Research limitations/implications: It would also be advisable to conduct additional research on all the influential factors and their interaction. The factors would appear on three or more levels, which would make it possible to show the non-linear dependence of the output, and to optimize the process itself.

Practical implications: The optimisation of injection moulding parameters gives better tolerances of both, the green parts and the sintered parts.

Originality/value: Not much research work has been done to examine the influence of injection moulding parameters in PIM. With these experiments we upgraded our existing knowledge about the influence of the injection-moulding parameters on the dimensional accuracy of the green part, made from stainless steel 316L, and thus contributed to improving the process's reliability.

Keywords: Metal injection moulding; Taguchi approach; Injection moulding parameters; Accuracy

1. Introduction

Experiments are necessary for the development of new products, for the introduction of new technologies and for improvements to known technologies. All experiments involve the costs of materials, the development of the measuring system, and the consumption of energy and time. The objective of a successful investigation is to obtain as much reliable information as possible about the process. For DOE different methods are used. In cases when one observes many inputs and interactions and there is also a time limitation the Taguchi approach is used for DOE.[1, 2, 3] The method is especially suitable for industrial use, but it can also be used for scientific research.

Powder injection moulding (PIM) is divided into four major technological phases: mixing, injection moulding, debinding and sintering. Each phase has an effect on the final part's characteristics. The parts made with PIM are near net shape

(NNS) or net shape (NS). However, this is possible only when all the technological phases have been mastered. It is used for injection of various materials like HSS [4, 5, 6], stainless steel [7], ceramics, carbides etc.

The majority of previous investigations have focused on the sintering parameters and the amount of metal powder in the mixture. Studies [8, 9] have shown that the shrinkage and the final dimensions are affected by the following sintering parameters: the rate of heating, the duration, the temperature of the sintering and the sintering atmosphere. The authors of [10] found that dimensional deviations after sintering decrease with a larger amount of powder in the mixture. Research [11] has shown a connection between the melt's viscosity changes and the dimensions of the green part. Other reports [12] have shown that the shape of the powder particles also has an effect on the dimensional deviations.

The effects of the injection parameters on the dimensional characteristics of green parts have not yet been thoroughly investigated. It was found [13, 14] that high holding pressure increases the dimensions and the mass of the product, while at the same time decreasing the surface subsidence. Tseng [15] established that the parameters that have the greatest influence on the part's dimensions, in terms of deviations from the nominal dimensions of the cavity, are the holding pressure and the powder-binder ratio. It was also established that the interaction between the holding pressure and the mould temperature has a great effect. Other studies [16] found that the holding pressure also has a certain effect on the shrinkage after sintering.

A review of the literature has shown that the majority of research was focused on the effects of the material and the sintering parameters on the geometrical accuracy. But studies have also shown that the injection-moulding parameters can have a certain influence. The dimensional deviations that occur during injection moulding cannot be rectified during the sintering process. Moreover, the deviations can often increase, which is the main reason why all the technological phases of PIM must be mastered. The objective of our experiments was to determine the effect of the injection-moulding parameters on the green parts' dimensions and mass and thus increase the reliability of the process.

2. Powder injection moulding

PIM is a combination of four sequential technological processes (mixing, injection moulding, debinding and sintering), all of which have an effect on the characteristics of the final parts. The scheme in Figure 1 represents the whole process. As part of the process of mixing the powder and binder the feedstock is made, which has to be as homogeneous as possible. In the next phase a green part is made by injection moulding. The green part is also a final product, but only, for example, when plastic-bonded magnets are produced. Then the binder is removed from the green part in various debinding processes. The brown part produced retains its shape due to the friction between the powder particles and their shape. This part is very fragile and needs to be sintered to achieve its final mechanical, chemical and dimensional properties. The final properties of the product can be further improved with mechanical, chemical and heat treatments.

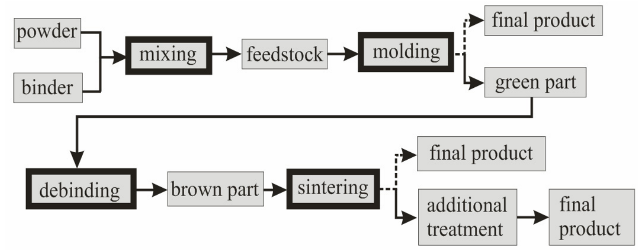

Fig. 1. Scheme of the powder injection-moulding process

3. Design of experiments

There are many injection-moulding parameters that have some effect on the properties of the green parts. Therefore, it is necessary to use one of the design of experiment (DOE) methods for the kind of experimental work where there are many inputs. The most frequently used methods are partial or full factorial design and the Taguchi approach. If an appropriate DOE is used, one can easily, relatively quickly and with a small number of trials, establish whether the inputs have an effect on the outputs of the system.

The Taguchi approach is mostly used in the industrial environment, but it can also be used for scientific research. The method is based on balanced orthogonal arrays. [1]

For the experiment we chose the OA L-16 (2^{15}). Fifteen main factors and interactions in two levels can be entered in the array (table 1). Based on the investigations [13, 15, 16] and the expertise of the injection-moulding process we chose six main parameters. Besides these parameters, which are controlled, there are also uncontrolled factors that have an effect on the process. Table 2 lists the uncontrolled and the controlled factors. The model of the injection moulding is shown in figure 2.

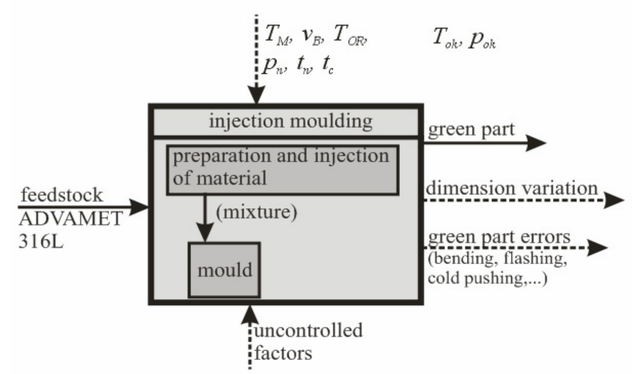

Fig. 2. The model of the process

For the DOE the following guidelines were taken into consideration: [17]

- the physical and engineering knowledge about the problem, because a statistic evaluation is not enough if the results are not evaluated properly.

Table 1.
L-16 orthogonal array

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
	A mm/s	C °C	AxC	D MPa	A x D	C x D	B °C	E s	F s	C x E	/	/	/	B x F	B x E
1	20	180	1	10	1	1	20	3	15	1	0	0	0	1	1
2	20	180	1	10	1	1	20	7	30	2	0	0	0	2	2
3	20	180	1	50	2	2	40	3	15	1	0	0	0	2	2
4	20	180	1	50	2	2	40	7	30	2	0	0	0	1	1
5	20	200	2	10	1	2	40	3	15	2	0	0	0	2	2
6	20	200	2	10	1	2	40	7	30	1	0	0	0	1	1
7	20	200	2	50	2	1	20	3	15	2	0	0	0	1	1
8	20	200	2	50	2	1	20	7	30	1	0	0	0	2	2
9	30	180	2	10	2	1	40	3	30	1	0	0	0	1	2
10	30	180	2	10	2	1	40	7	15	2	0	0	0	2	1
11	30	180	2	50	1	2	20	3	30	1	0	0	0	2	1
12	30	180	2	50	1	2	20	7	15	2	0	0	0	1	2
13	30	200	1	10	2	2	20	3	30	2	0	0	0	2	1
14	30	200	1	10	2	2	20	7	15	1	0	0	0	1	2
15	30	200	1	50	1	1	40	3	30	2	0	0	0	1	2
16	30	200	1	50	1	1	40	7	15	1	0	0	0	2	1

- the inputs of the system are defined on the basis of theoretical and practical knowledge.
- the outputs of the system must be selected in such a way that they provide useful information about the observed process.
- the design and analysis of the experiment must be as simple as possible.
- it is important to distinguish between the practical and statistical significance of the results – statistically significant results are not necessary practically significant.
- at the start of the study, when all the influential factors and their values are not known, it is not advisable to design too comprehensive an experiment. At the beginning the factors should be in two levels, in further investigations and during process optimization the factors should be in three or more levels.

Table 2.
The factors that have an effect on the injection-moulding process

Controlled factors	Uncontrolled factors
T_M – material temperature	Die shape
v_B – injection speed	Pressure drop
t_n – duration of holding pressure	Mould-temperature variation
p_n – holding pressure	Mixture homogeneity
t_c – cycle time	Material heating due to friction
T_{or} – mould temperature	Moisture in the material, etc.

Because of the possibility of the parameters interacting among themselves, we also observed the influence of six interactions. The parameter values and the interactions are shown in table 3. The values of the parameters were chosen to comply with the manufacturer's recommendations. The chosen temperature refers to the temperature of the machine nozzle.

Table 3.
Values of the parameters and interactions

	1	2	interactions
Injection speed A	20 mm/s	40 mm/s	AxC
Mould temperature B	20°C	40°C	AxD
Material temperature C	180°C	200°C	CxD
Holding pressure D	10 MPa	50 MPa	CxE
Holding pressure duration E	3 s	7 s	BxF
Cycle time F	15 s	30 s	BxE

The holding pressure and the holding-pressure duration are the factors that are supposed to have the biggest effect on the width and dimensions of the specimen. The holding pressure compresses the melt and fills the cavity because the binder contracts due to the cooling. The pressure has an effect until the gate solidifies. If the holding-pressure time is too short, slumps can occur on the surface.

The material's temperature has an effect on the viscosity of the melt and, consequently, on the ability of the melt to fill the cavity. If the melt's viscosity is too high, the parts will be unfilled. The temperature of the mould has an effect on the occurrence of internal stress, on the rate of cooling and on the ability of the melt to fill the die cavity.

The injection speed is an important factor because the die cavity has to be filled in a very short time. During the injection of the melt into the mould the melt solidifies on contact with the wall of the mould, which increases the pressure drop.

Table 4.
Chemical composition of stainless steel 316L

Material	Cr	Ni	Mo	C	Mn	Si	P	N	S	O
Share %	16.8	10.5	2.2	0.03	1.4	0.5	<0.01	0.18	<0.01	0.08

The effect of the parameters was investigated on a multipurpose specimen (Figure 3) used for tensile strength tests with polymer materials (ISO 3167). The used feedstock ADVAMET(R) 316L is a commercial product made by Advanced Metalworking. The mixture is composed of stainless steel 316L (Table 4) and binder, which is polymer-wax based.

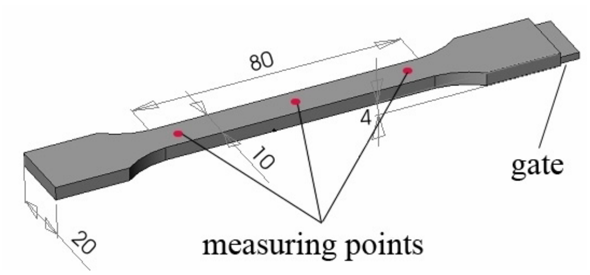

Fig. 3. The injection-moulded tensile-test strength specimen

The amount of binder is approximately 62 volume%, and the mixture's density is 5.301 g/cm^3. The powder particles are spherical and produced by gas atomization. The photograph of the spherical particles surrounded by the binder was taken with a camera mounted on an optical microscope at 500x magnification (Figure 4). The particle size is smaller than 45 µm; 80% of the powder particles are smaller than 16 µm. The viscosity of the melt is 827 Pas at a temperature of 175°C.

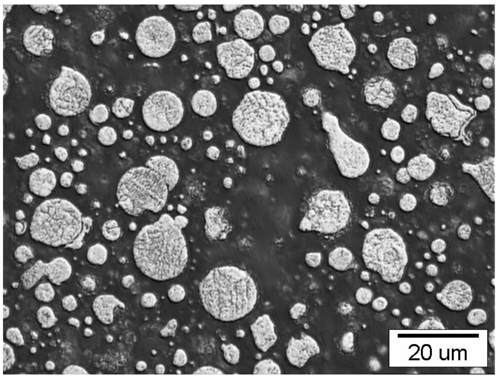

Fig. 4. Stainless steel (316L) powder particles, light microscope, etched with $FeCl_3$; 500x magnification

The specimens were injection moulded with a KraussMaffei KM50-220C. The experiments were conducted randomly. Seven specimens were made during each experiment: altogether there were 112 specimens. Because of the additional shrinkage the measurements of width and mass were made five days after the experiments. The width of the die cavity in the area of measurement is 10.124 ± 0.004 mm. The accuracy of the width measurement was ±0.002 mm, and that of the weighing was 0.1 g.

4. Statistical analysis

The results of the experiments were evaluated by the analysis of variance (ANOVA). [1] The main objective of the analysis was to determine the influence of every parameter on the variance of the results, regarding the total variance of all the parameters. This is defined by the sum of squares (equation 1). The calculation of ANOVA was made on the basis of the recommendations in [1].

$$SS = \sum_{i=1}^{N}\left(y_i - \bar{y}\right)^2 \quad oz. \quad SS = \sum_{i=1}^{N} y_i^2 - CF \tag{1}$$

SS sum of squares,
y_i value of each result,
CF correction factor.

$$CF = \frac{T^2}{N} \tag{2}$$

T the sum of all results,
N the total number of results.

To calculate the effect of an individual parameter on the variance a more useful equation is used:

$$SS_A = \frac{A_1^2}{N_{A1}} + \frac{A_2^2}{N_{A2}} + \ldots.. + \frac{A_n^2}{N_{An}} - \frac{T^2}{N} \tag{3}$$

A_1 the sum of results (y_i) where parameter A_1 is present,
N_{A1} number of experiments where parameter A_1 is present.

The following equations are needed for the calculation:

$$V_A = \frac{SS_A}{f_A} \tag{4}$$

V_A variance,
f_A degree of freedom of factor A.

$$F_A = \frac{V_A}{V_e} \tag{5}$$

F_A F ratio,
V_e variance of error.

$$P_A = \frac{SS_A}{SS} \tag{6}$$

P_A influence of factor A.

The degrees of freedom are an important part of the statistical analysis because they provide us with additional information about the process. The degrees of freedom for the Taguchi array are defined as follows:
DOF parameter = number of factor levels - 1
DOF experiment = number of results - 1
DOF error = number of all DOFs – number of DOFs of all parameters

For a quick evaluation of the process the sample standard deviation is calculated:

$$s(x) = \sqrt{\frac{1}{N-1}\sum\left(y_i - \bar{y}\right)^2} \tag{7}$$

s(x) sample standard deviation.

5. Results and discussion

5.1. The effect of the parameters on the width of the specimen

Table 5 shows that the injection-moulding parameters have a large influence on the specimen's dimensions. The smallest sample standard deviation of the width appeared in cases 3 and 15. However, the width in these two cases is not a maximum, which means that the cavity was not sufficiently well filled. The calculated shrinkage was in the interval from 0.9% (maximum width) to 1.7% (smallest width). The shrinkage shows that the injection moulding parameters have an important role when narrow tolerances need to be achieved. The largest specimen width was in case 16, while the sample standard deviation was 7 μm.

Table 5.
Mean width, sample standard deviation and shrinkage of the specimen

Exp. No.	$\bar{b}$ mm	*s(x)* *mm*	*ε* %	Exp. No.	$\bar{b}$ mm	*s(x)* *mm*	*ε* %
1	9.977	0.009	1.4	9	10.002	0.007	1.2
2	9.952	0.014	1.7	10	10.012	0.008	1.1
3	10.023	0.004	1.0	11	9.976	0.012	1.45
4	10.004	0.005	1.2	12	9.995	0.011	1.25
5	10.019	0.009	1.0	13	9.991	0.018	1.30
6	10.021	0.007	1.0	14	10.003	0.017	1.1
7	10.010	0.011	1.1	15	10.019	0.004	1.0
8	9.990	0.012	1.3	16	10.034	0.007	0.9

Table 6 shows only the influential parameters, which were determined by the ANOVA and F-test. The most influential parameters are the temperature of the mould, the temperature of the material, the holding pressure and the cycle time (Figure 5). The mould temperature has the biggest effect (46.7%): the higher the mould temperature the wider is the specimen. The same is true of the material temperature (20.8 %). The reason is probably that these materials have 10 times the thermal conductivity compared to the polymers. This means they cool very quickly in the mould. The mould temperature should be as high as possible so that the die cavity is evenly filled. At the same time the effect on the cycle time and on the conditions during ejection should not be too high. If the mould temperature was 55°C, the specimens would bend during ejection, although the cycle time was longer than 45 s. The recommended mould temperature for this material is 40–45°C.

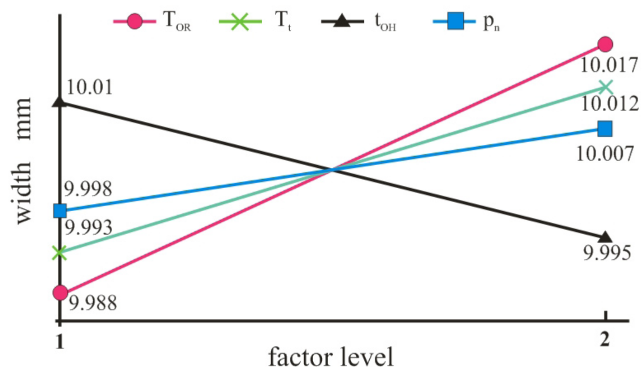

Fig.5.The influence of parameters on specimen's width

The confidence intervals are marked with stars:

* 95 % confidence interval,
** 99 % confidence interval.

The influence of holding pressure was expected, although the actual value was smaller than expected (13.3 %). Based on previous investigations [8] we expected that the holding pressure would have the biggest effect.

According to the experiments, the longer is the cooling time of the specimen in the mould, the smaller is the width of the specimen. It is known that when the cooling time of the specimen in the mould is too short, the specimen bends and the shrinkage is bigger due to large subsequent shrinkage[18, 19]. This is typical for crystalline thermoplasts, whose degree of crystallinity depends on the mould temperature and the rate of cooling (the cooling time in the mould). The higher is the cooling rate and the longer is the cooling time in the mould, the lower is the degree of crystallinity and the smaller is the shrinkage. Because of this the influence of the cooling time should be checked in the expanded experiments.

In general, the interactions between factors do not have any significant effect on the specimen's width. The interaction between the holding pressure and the material's temperature is shown in figure 6. When both factors are level 1, the width is the smallest, which means that the specimens are less filled. On the other hand, when both values of the parameters are level 2, the specimen is the widest.

Table 6.
ANOVA of the influential parameters for the specimen's width

parameters		Sum of squares	Degrees of freedom	Pure sum of squares	F - ratio	influence %
Mould temp.	B	0.0232	1	0.0232109	690.842954	46.69**
Material temp.	C	0.0103	1	0.0103309	307.485817	20.78**
Cycle time	F	0.0066	1	0.0065678	195.481980	13.21**
Holding pressure	D	0.0025	1	0.0024609	73.2467356	4.95**
	CxD	0.0010	1	0.0010020	29.8235461	2.01**
Other param.						5.65
	Error/other	0.0033		0.0000336		6.69
	Total	0.0497				100

Table 7.
ANOVA of the parameters influencing the specimen's width variation

Parameters		Sum of squares	Degrees of freedom	Pure sum of squares	F - ratio	Influence %
Mould temp.	B	3830.5804	1	3830.580	65.88845177	34.92**
Holding pressure	D	420.4375	1	420.438	7.231796062	3.83**
Injection speed	A	267.2232	1	267.223	4.596411568	2.43*
	AxD	261.0804	1	261.080	4.490750465	2.38*
Other param.						3.96
	Error/other	5755.598		58.137		52.48
	Total	10966.563				100

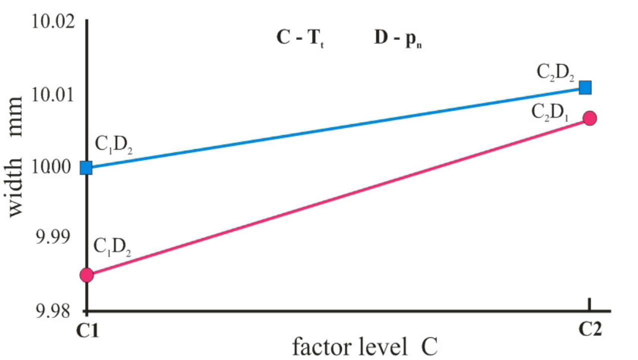

Fig. 6. Interaction between the material temperature (C) and the holding pressure (D)

5.2. The effect of the parameters on the width variation of the specimen

We observed the width variation in relation to the remoteness from the gate. It was found that the width variation is coincidental and does not depend on the remoteness from the gate.

Also in this case, the mould temperature has the biggest influence (34.9 %). The variation is smaller at higher mould temperatures. The injection speed and the holding pressure do not have such a big influence on the width variation. Due to small differences (3 μm) the influence of these parameters is only statistically significant; it has no practical significance. The temperature of the material has no effect, although some effect was expected (Table 7, Figure 7).

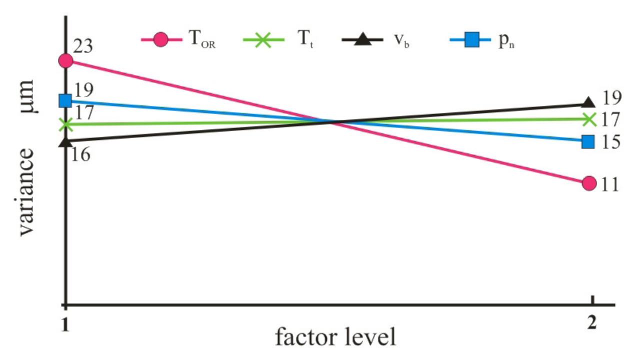

Fig. 7. The influence of parameters on the specimen's width variation

The experimental error was 52 %, but that does not mean the results are not valid. This means that there are other influential parameters (controlled and uncontrolled), which were not included into the experiment (mixture homogeneity, viscosity).

The interaction between the injection speed and the holding pressure is shown in figure 8. When the level of the injection speed is 1 the width variation is not influenced by the holding pressure. The combination of high holding pressure and high injection speed gives the smallest width variation.

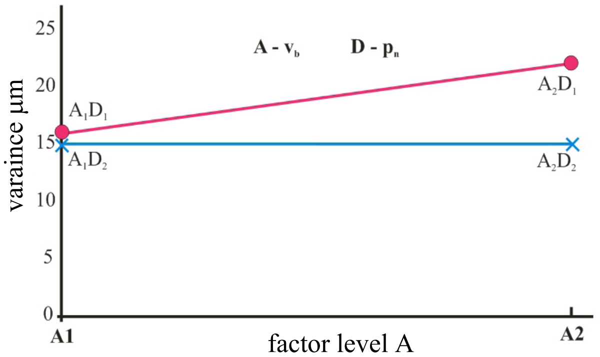

Fig. 8. The interaction between the injection speed (A) and the holding pressure (D)

5.3. The effect of the parameters on the mass of the specimen

The mass of the green part can tell us a lot about the process of injection. The die cavity should be filled as much as possible in order to minimize the possibility of the appearance of defects. The holding pressure should last until the mass of the green part is not increasing any more. Most of the parameters and also some of the interactions have an effect on the specimen's mass (Table 8). The holding pressure (44.8 %) has the biggest effect; the material temperature (19.7 %) comes second; these are followed by the effects of the injection speed (12.1 %) and the mould temperature (4.5 %). The influence of the parameters is shown in figure 9.

The mass is increased when all the parameter's values are in the second level. The effect of the holding pressure was expected, because when it is activated the die cavity fills and increases the mass of the green part. Because the part cools very quickly the injection speed and the material temperature also play an important role. A higher material temperature lowers the melt's viscosity, while a higher injection speed fills the die faster.

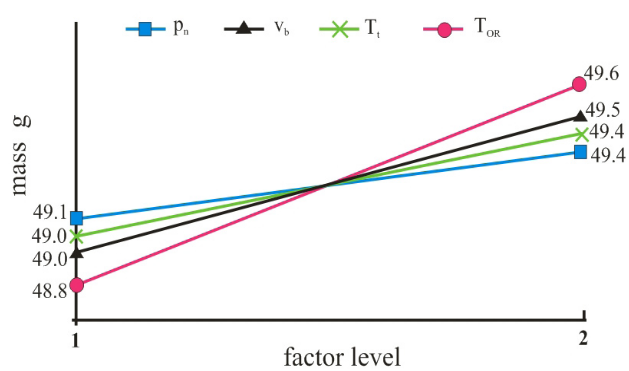

Fig. 9. The influence of parameters on the specimen's mass

The interaction between the material's temperature and the injection speed has a considerable effect on the mass (Figure 10). The green part has the highest mass when both parameters are in the second level and the lowest when they are in the first level. When the material's temperature is high (200°C) the injection speed has only a small effect on the mass.

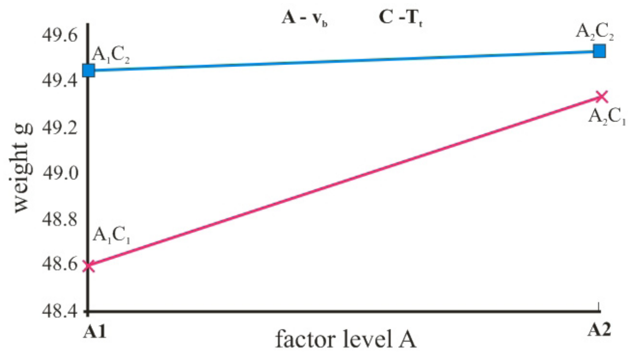

Fig. 10. The interaction between the injection speed (A) and the material's temperature (C)

The influence of the interaction between the holding pressure and the injection speed is similar (Figure 11). When the holding pressure is high (50 MPa) the injection speed has no effect on the mass.

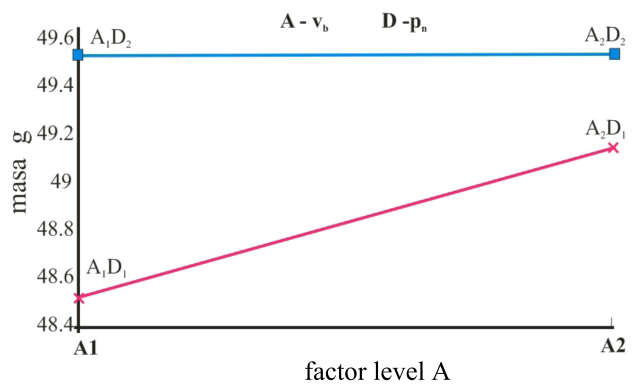

Fig. 11. The interaction between the injection speed (A) and the holding pressure (D)

6. Conclusions

With a small number of experiments it was established (with 99% probability) that the mould temperature has the biggest effect on the dimensions and dimensional variation of the green parts. The mould temperature for this feedstock should be from 40 to 45°C. At higher temperatures the parts stick to the mould and bend when they are ejected from the mould. The material temperature and the holding pressure also influence the width of the green part. The material temperature should be higher than 190°C, while the holding pressure should be increased to 80 MPa.

The effect of cycle time should be examined in additional experiments. Although the influence of the injection-moulding parameters on the width seems small it is very important to achieve the highest accuracy after the injection as possible, because the differences usually increase further after the sintering.

With these experiments we upgraded our existing knowledge about the influence of the injection-moulding parameters on the dimensional accuracy of the green part and thus contributed to improving the process's reliability.

The holding pressure, the material temperature and the injection speed have the biggest effect on the mass of the green part. When the values of the parameters are in the second level the mass increases, which has an advantageous effect on the characteristics after sintering.

In our future experiments we plan to examine the effects of injection parameters on the dimensions of the sintered products. It would also be advisable to conduct additional research on all the influential factors and their interaction, as well as the duration of the holding pressure. The factors would appear on three levels, which would make it possible to show the non-linear dependence of the output and to optimize the process itself.

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