World Academy of Science, Engineering and Technology
International Journal of Materials and Metallurgical Engineering
Vol:11, No:3, 2017

Material and Parameter Analysis of the PolyJet Process for Mold Making Using Design of Experiments

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Abstract**—**Since additive manufacturing technologies constantly advance, the use of this technology in mold making seems reasonable. Many manufacturers of additive manufacturing machines, however, do not offer any suggestions on how to parameterize the machine to achieve optimal results for mold making. The purpose of this research is to determine the interdependencies of different materials and parameters within the PolyJet process by using design of experiments (DoE), to additively manufacture molds, e.g. for thermoforming and injection molding applications. Therefore, the general requirements of thermoforming molds, such as heat resistance, surface quality and hardness, have been identified. Then, different materials and parameters of the PolyJet process, such as the orientation of the printed part, the layer thickness, the printing mode (matte or glossy), the distance between printed parts and the scaling of parts, have been examined. The multifactorial analysis covers the following properties of the printed samples: Tensile strength, tensile modulus, bending strength, elongation at break, surface quality, heat deflection temperature and surface hardness. The key objective of this research is that by joining the results from the DoE with the requirements of the mold making, optimal and tailored molds can be additively manufactured with the PolyJet process. These additively manufactured molds can then be used in prototyping processes, in process testing and in small to medium batch production.

Keywords**—**Additive manufacturing, design of experiments, mold making, PolyJet.

I. Introduction

RAPID technological changes and shorter product lifecycles in many industrial sectors demand a rapid time-to-market. In the field of mold making, time-to-market can be shortened by using additive manufacturing methods, such as the PolyJet 3D printing process. While the production of the molds accounts for approximately 34% of the time and 29% of the costs of mold making projects [1], the approach of additively manufacturing molding tools can lead to cost and time savings. In a survey that was conducted by the Chair of Production Engineering of E-Mobility Components (PEM) of RWTH Aachen University about the use of additive manufacturing methods in the tool making and plastics industry, 35 experts were interviewed [2]. The survey revealed that on average, it takes 7.6 weeks to conventionally produce a new molding tool. In this process, 1.56 pre-series molding tools will be produced in 3.8 weeks. The production time of the molding tool accounts for 72% of the tool development process. Furthermore, an average of 2.6 different production processes is used with 9.4 changeover procedures and 4.8 workers. In the survey, 50% of the participants are convinced that additive manufacturing methods, such as the 3D PolyJet printing process, could already be used for mold making for prototype and small series production. The survey also showed that surface roughness and dimensional accuracy are considered the most important features of a molding tool. Especially for the PolyJet 3D printing process, 85.7% of the participants say that intensive research could lead to the technological maturity for mold making applications. [2]

Because of its large build tray, its high accuracy of up to 600 μm and the fact that it processes thermosetting materials, the PolyJet 3D printing process is generally suited for mold making applications. Due to a high amount of different printing parameters and materials, a profound understanding of the interdependencies is needed to be able to additively manufacture molds that perfectly match the individual requirements of the thermoforming or injection molding process.

Thus, the goal of this research is to determine the interdependencies between different printer parameterizations and materials in the PolyJet 3D printing process and the printed part's mechanical properties by using a full factorial DoE. A qualitative comparison between printed specimens should produce reliable information about the cause-effect relationship of the 3D printer's parameterization. The results will then be combined and transferred into a process configuration tool, which will propose the optimal parameterization and material choice for individual tool requirements.

II. Hardware and Methodology

A. Hardware

The 3D printer used and analyzed within this research is the PolyJet printer *Connex2 Objet 500* by Stratasys Ltd. Its specifications can be found in Table I.

The PolyJet technology itself is described in the patent EP 1274551 B1 [4]. As described by Gebhardt, PolyJet 3D printing is an additive manufacturing process that was developed by Objet Geometries [5]. In the manufacturing process, layers of an acrylic-based photopolymer are

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selectively jetted onto a build tray via inkjet printing (Fig. 1). The jetted photopolymer droplets are immediately cured with ultraviolet lamps that are mounted onto the jetting head.

TABLE I
OBJET 500 SPECIFICATIONS [3]

Net build size	490 mm x 390 mm x 200 mm
Layer thickness	34 µm; 16 µm
Build resolution	600 dpi (X-axis) 600 dpi (Y-axis) 1600 dpi (Z-axis)
Printing modes	Digital Material (30 µm) High Quality (16 µm) High Speed (30 µm)
Accuracy	85 µm for features smaller than 50 mm 600 µm for full model size
Size	1960 mm x 2868 mm x 2102 mm
Weight	430 kg
Number of printing heads	8

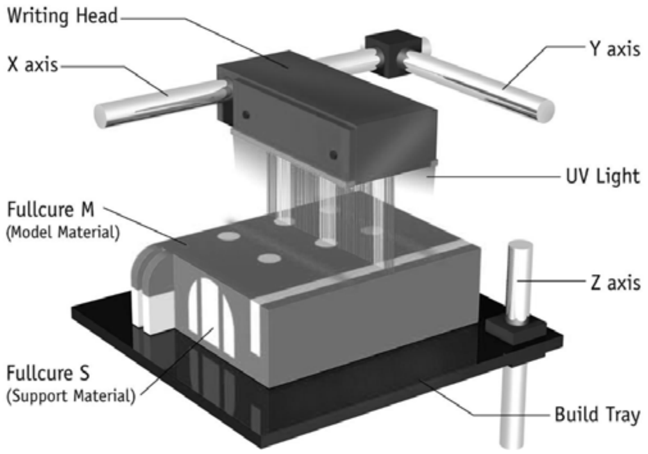


Fig. 1 PolyJet principle [4]

B. Methodology

The methodology of this research can be divided into four gradual steps:

1. Identification of requirements of molding tools
2. Definition of printing parameters and materials
3. DoE
4. Evaluation of the results and creation of a software tool

In the first step, the mechanical and thermal requirements of molding tools are identified. Then, the parameters and materials to be analyzed will be defined. Based on the identified requirements and the defined parameters, a full factorial trial design will be created and the data will be collected. The evaluation of the results and the creation of an advising software tool conclude this research.

III. IDENTIFICATION OF REQUIREMENTS

In order to successfully manufacture molding tools of high quality and durability, the mechanical and thermal requirements of these tools have to be identified at first. The requirements include the tensile strength, the tensile strength at higher temperatures, the surface roughness, the surface hardness and the size accuracy or dimensional deviation [6], [7]. Since molding tools are often subject to high forces or pressure, the tensile strength is an important characteristic [8].

Depending on the molding technology, the molding tool has to withstand relatively high temperatures (Table II), which in the case of additively manufactured molding tools made from plastic material, can lead to a malfunction of the tool. Therefore, the tensile strength at higher temperatures (i.e. 35 °C) is examined.

The surface hardness (Shore D) and roughness (R_a) directly correlate with the quality of the product to be molded, thus these requirements must be examined as well.

Ultimately, the dimensional accuracy or dimensional deviation (measured in µm) need to be determined to guarantee the adherence of measurements.

TABLE II
PROCESS PARAMETERS OF DIFFERENT PLASTIC PROCESSING TECHNOLOGIES

Technology	Tool temperature [°C]	Material temperature [°C]	Pressure [bar]
Injection molding	50-80	200-400	600-800
Rotational molding	200-400	200-400	0
Blow molding	60-85	100-200	0-10
Thermo-forming	60-85	100-200	0-7.5

IV. DEFINITION OF PARAMETERS

The definition of printing parameters and materials is necessary for the creation of a trial design for the DoE. The parameters that were examined can be separated into two categories: printing materials and process parameters.

A. Printing Materials

Stratasys Ltd. offers 25 different PolyJet materials, of which 3 are not available for the Objet 500 printer. The remaining number of 22 materials is still too high, since an examination of all materials would be cost-intensive and time-consuming. Therefore, the number of materials must be systematically reduced. This happens with two approaches. Materials with identical material properties will be grouped into material families and only one of these materials will be used as a reference material. Materials with high tensile strength and high surface hardness that suit the requirements for mold making applications are preferred. Thus, rubber-like materials are excluded from this research. Bio-compatible material MED610 and high temperature material RGD525 are also excluded, since their scope of application is not within rapid tooling [9]. The material selection was based on the material specifications and the PolyJet Material Selection Guide provided by Stratasys Ltd. [10], [11]. By grouping the materials into families, comparing them and choosing the one with the best specifications, the number of materials to be tested was reduced to four: *Digital ABS Ivory*, *VeroGray, RGD720* and *Rigur*, as Fig. 2 illustrates.

B. Process Parameters

Besides the choice of materials, various printer settings need to be set to operate the printer. Since the printer's configuration is highly determined, only the following parameters can be set. These settings include the surface finish, i.e. the surface qualities. The *surface finish* can either be *matte* or *glossy*. Next the support material needs to be set from the options *lite*, *standard* and *heavy*. The factor *support material* determines the amount of support material used. Then the *printing mode* needs to be set. There are three printing modes to choose from: *High speed*, *high quality* and *digital material*. As for digital materials, only the printing mode *digital material* is available. Other materials can be printed either in the *high quality* or *high speed* mode.

Bio-compatible and Dental		Engineering Plastics		Standard Plastics			
Bio-compatible	Dental	Digital ABS	High Temperature	Transparent	Rigid Opaque	Simulated Poly-propylene	Rubber-like
MED610	VeroDent	**Digital ABS Ivory**	RGD525[E]	**RGD720**	**VeroGray**	Durus	TangoPlus[D]
	VeroDent Plus	Digital ABS Green[A]		VeroClear[B]	VeroBlack Plus[B]	**Rigur**	TangoBlack[D]
	VeroGlaze	Digital ABS2 Ivory[A]			VeroPure-White[B]		TangoGray[D]
		Digital ABS2 Green[A]			VeroWhite Plus[B]		TangoBlack Plus[D]
					Vero-Yellow[B]		
					VeroCyan[B]		
					VeroMagenta[B]		
					VeroBlue[C]		

☒ = not available for the Objet500
☐ = excluded
A = identical properties as Digital ABS Ivory
B = identical properties as VeroGray
C = inferior mech. properties to VeroGray
D = insufficient mech. properties
E = inferior properties to Digital ABS according to the PolyJet Material Selection Guide
F = inferior mech. properties to Rigur

Fig. 2 PolyJet materials

TABLE III
FACTORS AND FACTOR LEVELS OF THE DOE

Factor	Low factor level	High factor level
Surface finish	Matte	Glossy
Support material	Lite	Heavy
Printing mode	High Speed	High Quality
Part orientation	0°	90°
Thermal post-treatment	None	Type B

Besides the printer settings, there are two more parameters that influence the characteristics of the printed part: The *orientation* of the printed part on the build tray and the optional *thermal post-treatment* of the printed part, which is applicable to Digital ABS only. Initial analyses showed that different orientations of the part result in different mechanical properties, therefore the influences of the orientation of the part need to be investigated. According to [12], thermal post-treatment can positively influence the heat deflection temperature of the printed parts. Influences on other mechanical properties, e.g. the tensile modulus, may occur as well.

V. ANALYZING PARAMETER AND MATERIAL INTERDEPENDENCIES USING DOE

After identifying the requirements of molding tools and defining the process parameters of the printing process, the influences and interdependencies of the parameters are analyzed with a DoE. DoE is a systematic method to determine the relationship between factors (i.e. parameters) affecting a process and the output of that process.

For the DoE, factors and factor levels must be defined. Based on the defined parameters in Chapter IV, the factors and their levels have been determined. They are listed in Table III.

With the factors determined, a trial design is created for each material. Each trial design contains the factors *surface finish*, *support material* and *part orientation*. Notice that *part orientation* varies between 0° and 90° only. This is due to the assumption, that 0° and 180° as well as 90° and 270° part orientation behave in the same way. Furthermore, by adding more orientation angles the trial design would exponentially grow. The examination of angles between 0° and 90° should thus be part of further researches. The trial designs for *VeroGray*, *Rigur* and *RGD720* additionally contain the factor *printing mode*. The trial design for *Digital ABS Ivory* additionally contains the factor *thermal post-treatment*. Consequently, each trial design contains four factors with two factor levels. According to (1) each trial design consists of 16 single tests [13].

$$n_r = n_l^{n_f} \tag{1}$$

n_r: *number of tests*
n_l: *number of factor levels*
n_f: *number of factors*

Fig. 3 exemplary illustrates the trial design for the material VeroGray.

Pattern	Surface finish	Part orientation	Support material	Printing mode
1111	Matte	0°	Lite	High Speed
1112	Matte	0°	Lite	High Quality
1121	Matte	0°	Heavy	High Speed
1122	Matte	0°	Heavy	High Quality
1211	Matte	90°	Lite	High Speed
1212	Matte	90°	Lite	High Quality
1221	Matte	90°	Heavy	High Speed
1222	Matte	90°	Heavy	High Quality
2111	Glossy	0°	Lite	High Speed
2112	Glossy	0°	Lite	High Quality
2121	Glossy	0°	Heavy	High Speed
2122	Glossy	0°	Heavy	High Quality
2211	Glossy	90°	Lite	High Speed
2212	Glossy	90°	Lite	High Quality
2221	Glossy	90°	Heavy	High Speed
2222	Glossy	90°	Heavy	High Quality

Fig. 3 Trial design for VeroGray

	Digital ABS Ivory		Rigur	
	Structural strength (MPa)	Surface hardness (Shore D)	Structural strength (MPa)	Surface hardness (Shore D)
Minimum	52,50	79,28	34,68	73,77
Maximum	59,81	82,94	40,29	77,55
Mean	57,02	81,13	38,22	75,58
Standard deviation	2,35	1,42	1,58	1,57
Stratasys Ltd. data	50 - 60	85 - 87	40 - 45	80 - 84

	VeroGray		RGD720	
	Structural strength (MPa)	Surface hardness (Shore D)	Structural strength (MPa)	Surface hardness (Shore D)
Minimum	54,91	77,91	53,41	76,76
Maximum	60,75	81,59	60,26	80,78
Mean	58,01	79,94	57,03	78,94
Standard deviation	1,54	1,57	2,32	1,64
Stratasys Ltd. data	50 - 65	83 - 86	50 - 65	83 - 86

Fig. 4 Experimental data compared to Stratasys Ltd. data

For each material, 16 different tests have to be performed. To determine the tensile strength, tensile tests conforming to DIN EN ISO 27 are performed [14]. To avoid incorrect results due to incorrect measurements, five specimens must be tested and the results will be averaged. In total, 640 specimens must be printed and tested. This number results from 4 different materials with 5 small sized specimens for the high temperature tensile tests and 5 standard sized specimens for the standard tensile tests, and 16 variations per specimen (see Fig. 3). The surface hardness is quantified with a Shore D hardness test whereas the surface roughness (R_a) is measured with a surface profiler. The tensile strength at higher temperatures is examined with a tempered tensile testing machine and the dimensional deviation is examined with an optical microscope.

Fig. 4 shows the measured minimum values, the maximum values, the mean values, the standard deviation and the value ranges provided by Stratasys Ltd. in [10] of the structural strength and the surface hardness. As it can be seen in Fig. 4, the structural strength measured for all four materials approximately corresponds with the material data provided by Stratasys Ltd. However, the surface hardness measured is lower than indicated by Stratasys Ltd. for all four materials.

Since Stratasys Ltd. only provides a range of material properties without suggesting any parameterization, the main challenge for the user is to set up the printer to reach the best results regarding their requirements towards the printed part.

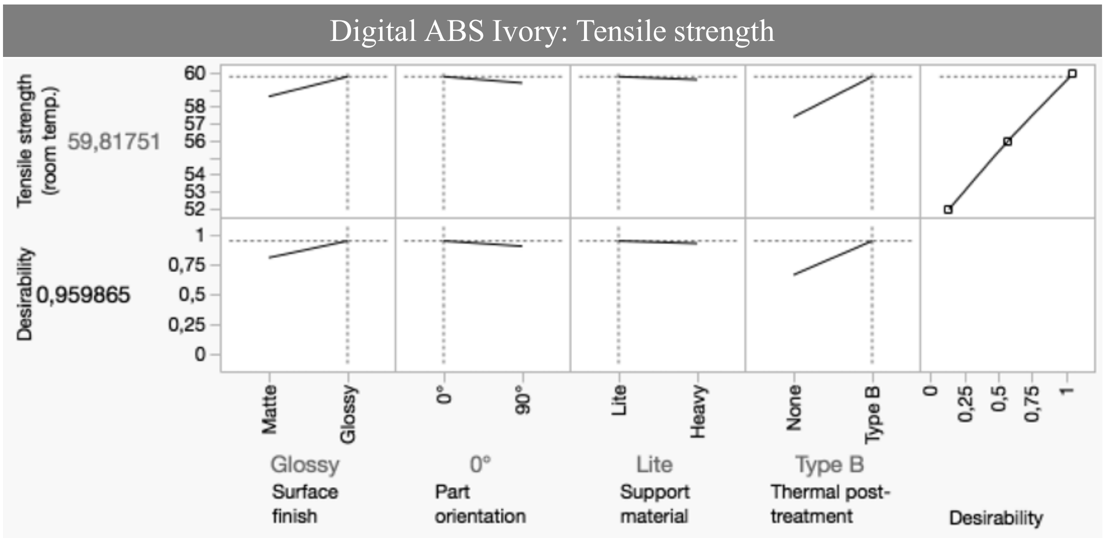
Fig. 5 shows the minimum values, the maximum values, the mean values and the standard deviation for the surface roughness, the dimensional deviation (width and height) and the structural strength at 35 °C for all measurements obtained in this research.

	Surface roughenss (µm)	Dimensional deviation, width (µm)	Dimensional deviation, height (µm)	Tensile strength at 35°C (MPa)
	Digital ABS Ivory			
Minimum	0,20	-96,17	-86,33	43,13
Maximum	4,84	263,50	-4,83	56,29
Mean	2,12	78,88	-43,86	49,44
Standard deviation	1,58	108,48	22,28	4,46
	VeroGray			
Minimum	0,18	-89,33	-85,89	25,33
Maximum	3,71	162,17	32,00	34,73
Mean	1,74	43,66	-31,44	30,49
Standard deviation	1,24	83,84	32,35	2,44
	Rigur			
Minimum	0,20	-49,50	-109,00	19,95
Maximum	4,10	93,33	12,00	25,01
Mean	1,76	38,40	-38,55	22,01
Standard deviation	1,30	49,38	31,81	1,46
	RGD720			
Minimum	0,17	-129,50	-71,33	22,17
Maximum	5,86	201,83	48,67	31,11
Mean	2,29	67,26	-15,98	26,88
Standard deviation	1,72	106,81	33,17	2,35

Fig. 5 Experimental data

To understand the interdependencies of the factors or parameters and to perform the statistical evaluation of the DoE, the statistical discovery software JMP 13 by SAS is used. The main goal is to identify statistically relevant factors or effects and to understand their impact on the printed part's properties. The DoE was modelled using a "Standard Least Squared" behavior. Each effect and interaction had its F-ratio calculated and compared against the critical F-ratio calculated at an alpha-value of 0.05.

Fig. 6 exemplarily shows the ANOVA (i.e. analysis of variance) for tensile strength of Digital ABS Ivory to the second factorial degree with optimized desirability (maximum tensile strength). The maximum tensile strength is achieved by using the parameterization Glossy (surface finish), 0° (orientation), Lite (Support material) and Type B (thermal post-treatment). For tensile strength of Digital ABS Ivory, surface finish, support material and thermal post-treatment are statistically significant main effects and surface finish*support material and surface finish*thermal post-treatment are statistically significant interaction effects.



Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Surface finish	1	1	32,049638	194,4325	<,0001*
Part orientation	1	1	0,465227	2,8223	0,1538
Support material	1	1	1,922360	11,6622	0,0189*
Thermal post-treatment	1	1	41,930664	254,3768	<,0001*
Surface finish*Part orientation	1	1	0,000012	0,0001	0,9936
Surface finish*Support material	1	1	2,700021	16,3800	0,0099*
Part orientation*Support material	1	1	0,131320	0,7967	0,4130
Surface finish*Thermal post-treatment	1	1	2,804847	17,0159	0,0091*
Part orientation*Thermal post-treatment	1	1	0,089760	0,5445	0,4937
Support material*Thermal post-treatment	1	1	0,061991	0,3761	0,5665

Fig. 6 ANOVA for tensile strength of Digital ABS Ivory

While in Fig. 6 only one property was optimized regarding desirability (tensile strength), the software also allows the simultaneous optimization of several properties, so that for each material an optimal parameterization with regard to the optimization goals (Table IV) can be calculated. Notice that for surface roughness, the optimization goal depends on the field of application of the printed part. While some tools demand a smooth surface, other tools might require a rather rough surface.

TABLE IV
OPTIMIZATION GOALS

Property	Optimization goal
Surface roughness	Individual optimization goal
Dimensional deviation (width)	Minimize
Dimensional deviation (height)	Minimize
Tensile strength	Maximize
Surface hardness	Maximize

Fig. 7 illustrates the ANOVA and the optimal parameterization for VeroGray in the case, that all properties should be optimized. The optimal parameterization is given by Glossy, 90°, Heavy and High Speed. In this model, surface finish, part orientation and printing mode are statistically significant main effects and surface finish*part orientation and support material*printing mode are statistically significant interaction effects.

The gradients of the lines in Fig. 7 indicate their relevance for the properties. As it can be seen, changing the surface finish from glossy to matte results in higher changes in every property's value than changing the support material from heavy to light.

The above shown analyses have been performed for all four materials. Thus, Fig. 8 shows the optimal parameterization for all four materials in the case, that all six target properties have been optimized equally.

Fig. 8 clearly shows that a glossy surface finish, a 90° part orientation and thermal post-treatment or high speed printing mode result in the best printing part's properties in the case that all target properties have been optimized. However, as Fig. 6 indicates, when focusing on the optimization of single properties, other parameterizations might be advantageous, like the 0° part orientation in this special case.

For all four materials, surface finish was a statistically significant effect on the tensile strength, with higher tensile strength values for glossy finishing.

Due to the high amount and the complexity of information gathered, a software tool has been created with MATLAB. The key objective of this tool is to recommend the best suiting parameterization of the printer and material choice to match individually requirements of the printed part. The concept of this software tool is illustrated in Fig. 9. The results of the DoE are stored in an Excel data sheet. This data sheet can be imported into the software that is designed and programmed with MATLAB. In a graphical interface, the user can enter individual requirements of the printed part, e.g. a value for the surface hardness etc. The software then calculates the best suiting parameterization according to the data gathered in the DoE.

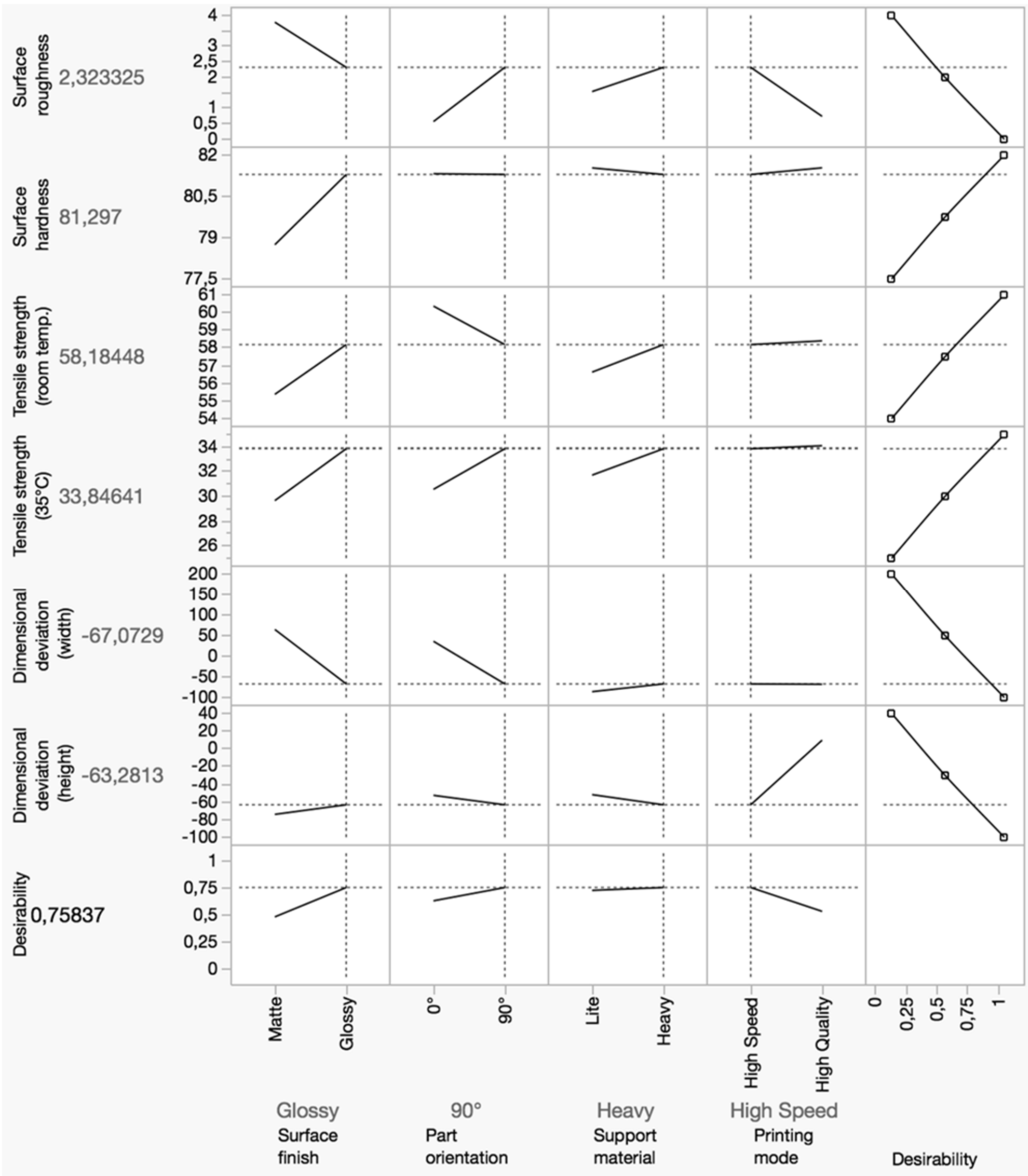


Fig. 7 VeroGray ANOVA

Material	Surface finish	Part orientation	Support material	Thermal post-treatment	Printing mode
Digital ABS	Glossy	90°	Lite	Type B	-
VeroGray	Glossy	90°	Heavy	-	High Speed
Rigur	Glossy	90°	Lite	-	High Speed
RGD720	Glossy	90°	Lite	-	High Speed

Fig. 8 Optimal printer parameterization

Fig. 10 shows the graphical user interface and an exemplary utilization of the software tool. The software is able to suggest a set of parameters that best match the requirements, and it also suggests alternative parametrizations, in case the first suggestion cannot be used.

VI. Summary and Conclusion

In the framework of this study, the PolyJet 3D printing process was examined in detail. With the use of DoE, the interdependencies of different parameters and materials as well as the cause-effect-relationships have been determined. The results from the DoE have then been implemented into a software tool, with which it is possible to identify the optimal parameterization for individual requirements regarding the printed part. The main goal was to be able to additively manufacture molding tools that endure the typical process influences, such as high temperatures, pressure and forces. By having analyzed the requirements of molding tools and the interdependencies of the printer parameterization, tailor-made molding tools can be printed with the Connex2 Objet 500. The results of this study form profound and fundamental basics in the field of PolyJet 3D printing and the individual parametrization of the printer.

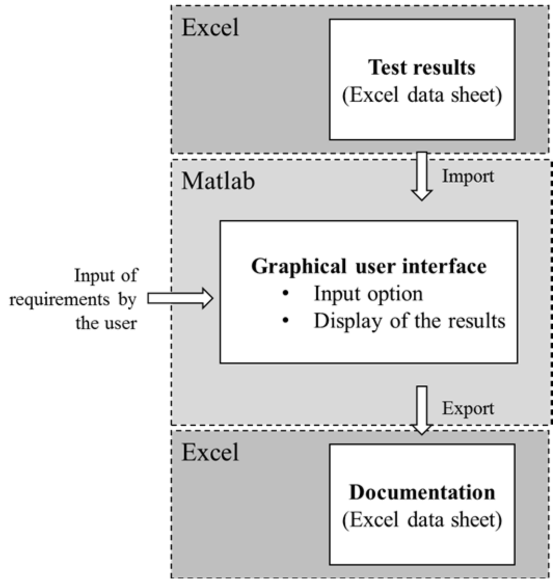


Fig. 9 Concept of the software tool

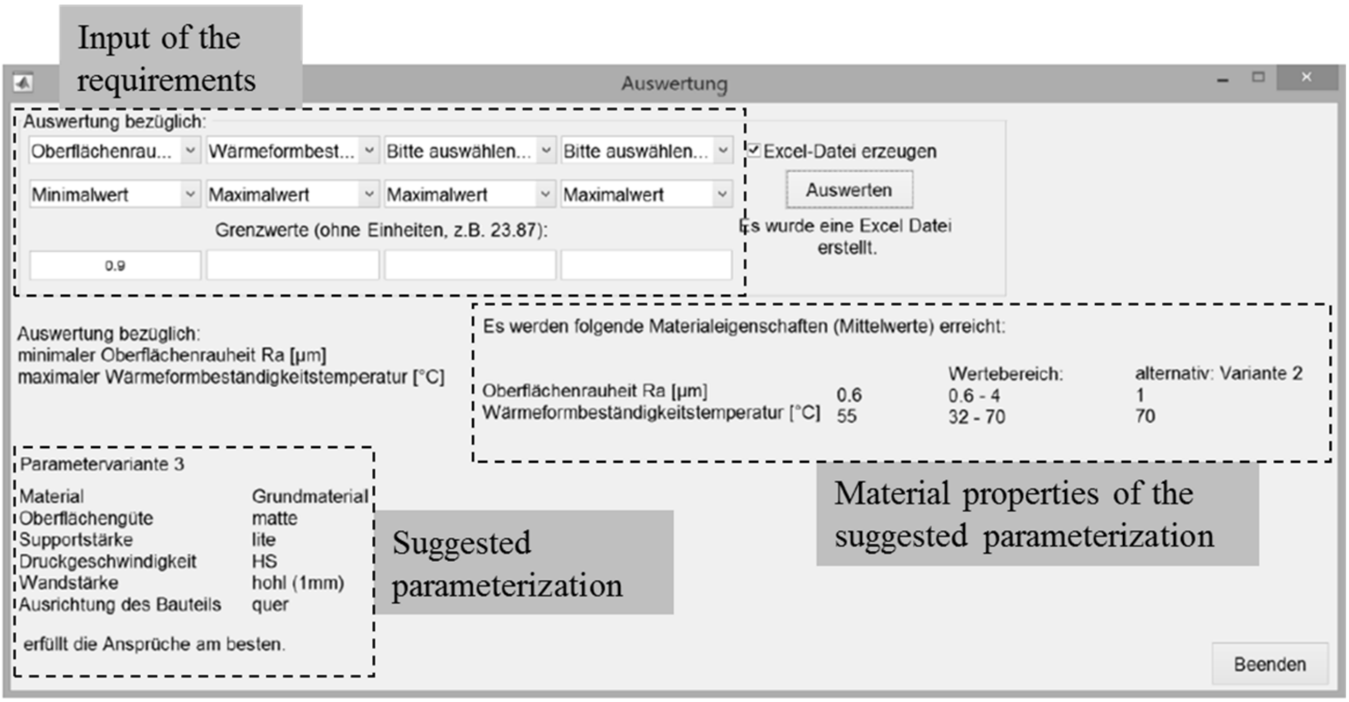


Fig. 10 Graphical user interface of the software tool

Acknowledgment

The presented approach has been designed by the Chair of Production Engineering of E-Mobility Components (PEM) of RWTH Aachen University and the Laboratory of Machine Tools and Production Engineering (WZL) within the publicly funded research project Anlauffabrik II, funded by the federal ministry for economic affairs and energy of Germany.

The authors acknowledge Mirko Bezema and Lukas Krüger for their assistance with testing the specimen and Sven Windau for his assistance in evaluating the obtained measurement results.

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