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EFFECT OF PARAMETERS OF THE STEREOLITHOGRAPHY PROCESS ON THE PART QUALITY

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Abstract: This paper investigates the effect of additive manufacturing parameters on the manufacturing quality of selected gear mechanism components. Three input variables, and two output variables were determined. The result was the determination of the most optimal combination of key parameters and the determination of regression equations. The concept of manufacturing objects of a very complex shape, by any person, under various conditions through the use of a low-cost device became the basis for this thesis topic. Curing time, layer thickness, and lift speed are among the basic parameters, with a large range of manipulation. A hypothesis was formulated that these three parameters are crucial to produce a part with the smallest possible deviations from the computer model. A handheld scanner was used to scan the samples and compare them with the CAD model. Based on the study, optimal parameters for layer thickness, curing time and lift speed were proposed.

Keywords: SLA, stereolitography, 3D scanning, process parameters, curing time, layer thickness, lift speed

1. INTRODUCTION

Additive manufacturing, also known as 3D printing, is a set of additive methods for producing three-dimensional parts. Their essence is the cavity-free production of parts, or entire products, based on their computer model. A common feature of these techniques is obtaining a finished object by adding and bonding successive layers of material one by one until a fully finished part is obtained. This is a very rapidly developing branch of technology, with changes occurring constantly. This demonstrates the very high potential of additive manufacturing.

Additive manufacturing has very many advantages, Dodziuk [1] lists, among others, such as:

- freedom of geometry of manufactured items,
- the ability to personalize products, e.g. prostheses, implants, jewelry,
- rapid prototyping,
- the very large number of materials used,
- the possibility of unit production without running a production line,
- rapid application of changes in the projection of the object.

1.1. Additive technologies

There are several leading additive manufacturing technologies. Each is characterized to some extent on a different method of operation or material used. Jordan [2] lists as major technologies:

- Fused Deposition Modeling (FDM) - Parts are created by applying layer upon layer of semi-fluid thermoplastic material,
- SLM selective laser melting (Selective Laser Melting)/ DMP direct metal printing (DMLS Direct Metal Laser Sintering) - manufacturing using metal powders melted by a laser beam,
- SLS selective laser sintering - technology based on sintering polymer powders,
- CJP color jet printing (CJP) - printing using colored gypsum powders,
- SLA stereolithography / DLP digital light processing - UV light curing of photo-curable resin.

These are just some of the most popular technologies. There are very many types of them, some of which are not directly applicable to industry.

It would be worth mentioning bio-printing, additive manufacturing using concrete, or food.

As you can see, each of the listed technologies is named using three-letter acronyms. These are formed from their names given in English, e.g. FDM (Fused Deposiotion Modeling). The multiplicity of names and the slight similarities between the various groups of manufacturing methods are due to marketing reasons, among others. There are times when the same technologies have different trade names, e.g. FDM and FFF - Fused Filament Fabrication.

Additive manufacturing can have a wide range of applications, it is a set of techniques that allow the production of items impossible to manufacture using other manufacturing methods. It allows the realization of projects whose only limitation is the creativity of the creator.

1.2. Stereolitography (SLA)

One of the major categories of additive manufacturing techniques, according to English-language literature, such as Redwood et al. [3], is vat polymerization. Stereolithography (SLA or STL), a component, advancement, or subdivision of DLP (depending on the source), is the dominant technique. One of the earliest technologies of this kind, it entails employing ultraviolet (UV) radiation to solidify the beginning material. The two primary categories of devices are. In the first, mirrors are used to reflect UV rays onto the surface from above, whereas in the second, light is directed from below.

The material used is a photopolymer resin, the chemical composition of which may vary depending on its intended use and is usually undisclosed by the manufacturer. Resins come in many varieties, such as universal, high-strength, flexible, dental/medical, casting, and so-called modeling resins (used for precision components). There are several additional subcategories, but they may be considered highly specialized.

Before starting the manufacturing process, necessary preparations must be made. The authors of [2] specify nine steps that need to be taken to obtain a properly prepared file, which the device will use to produce the designed element.:

1. Preparation of the CAD model.
2. Conversion to .stl format.
3. Checking and repairing the .stl file.
4. Generating supports.
5. Slicing into layers.
6. Transformation into a numerical model.
7. Preparation of the G-code.
8. Data control and analysis.
9. Final processing of the finished file.

The first stage is designing a three-dimensional model of the planned element. The more accurate it is, the higher quality the resulting object will be. Additive manufacturing enables the production of elements that are impossible to make using other methods. The model can have empty spaces, protruding elements of various geometries, and many other unconventional solutions. This is done using any computer-aided design (CAD) software, such as "Autodesk Inventor".

The finished design must be saved in the ".stl" format. This is a way of representing 3D graphics in the form of a three-dimensional mesh of triangles. Each vertex of the triangles is described by three coordinates. None of them can be located on the edge of the opposite triangle, only forming nodes with other vertices [4].

The finished model is then processed in software such as "slicer" programs like "CHITUBOX" or "Slic3r," or dedicated software specific to the particular device. Their task is to directly prepare the 3D model for the manufacturing process. The result of such a program is a g-code that is used to define the device's work. It can be sent directly to the device via the internet or Bluetooth, or in other cases transferred using an appropriate data carrier such as a memory card. During the project development, many parameters are determined, including:

- the thickness or number of layers,
- the size of the work area,
- the position of the model on the platform,
- the properties of the resin, such as density,
- the type of supports,
- other more detailed parameters.

Working in this type of program begins with determining the position of the element on the work platform. Redwood and co-authors [3] state that the orientation can be arbitrary in some cases, but considering the fact that the material used is liquid resin, the object should be positioned in such a way that the resin can easily flow over the object during the printing process.

In Figure 1 (CHITUBOX V1.6.1. 2022), we can see a fragment of the interface of a "slicer" software, namely CHITUBOX V1.6.1. It shows the moment of designing supports. One can notice a significant number of variables that need to be inputted, such as the diameter of the support, contact segment parameters, and many others. There is also an option for automatic support generation. "Slicer" programs allow for a very flexible approach to preparing the additive manufacturing process. On the one hand, they are highly automated, but on the other hand, they allow for very precise setting and editing of all relevant parameters.

In the case of this technology, the support system is of great importance. According to Redwood and co-authors [3], any part of the element that protrudes beyond the main solid adjacent to the base, positioned above 45˚, should be supported by them. However, it is not always possible to apply this rule, as the type of material, layer thickness, and type of device used have a significant impact on this aspect. Therefore, in some cases, this angle may be greater than 45˚, while in others, it may be smaller.

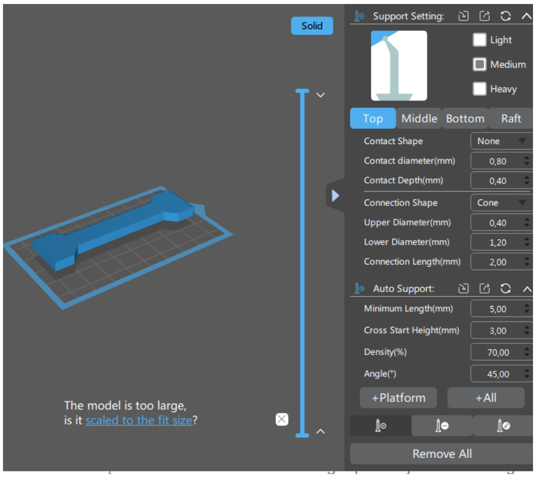

Fig. 1. Example of a "slicer" software interface

The supports in this technology are made of the same material as the entire object. Their shape largely depends on the technology used. In the case of stereolithography, they are cylindrical elements tapering at the end with a clear contact point. Linear supports and tree-shaped supports are distinguished, and both types are shown in Figure 2. Their application depends on the required height; the larger the value, the higher the probability of using more complexly shaped supports [5].

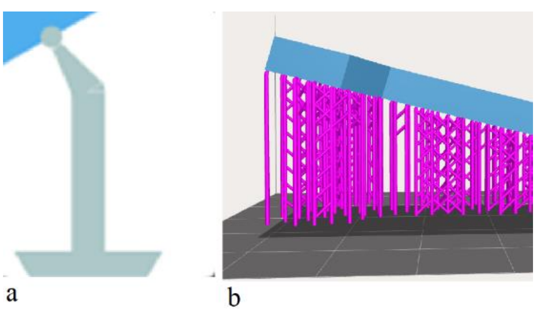

Fig. 2. Types of supports. a) Linear support b) Tree-like supports

Supports generate additional costs. Their production requires an extra amount of material and the process takes more time. Additionally, there is the removal of supports and finishing work on the surface they were attached to.

The next step is to slice the model into layers. The thickness or number of layers is determined and the program generates them, and based on them, creates the G-code.

The authors of publication [6] describe the process of additive manufacturing in a bottom-up orientation system. The process starts with the work platform immersed in a vat containing photopolymer resin. Then, the first layer is cured on the platform using ultraviolet radiation. Next, the platform is raised, and the same method is used to apply the next layer directly on top of the previous one. The process continues until the object is completely manufactured.

Usually, the layer thickness ranges from 10 to 100 µm, but this is not a rule. The smaller this value, the better the reproduction of the object's geometry, but on the other hand, the production process is prolonged, which is directly related to the cost. Conversely, increasing the thickness will have the opposite effect.

Once the object is printed, it needs to undergo post-processing. The support structures are removed, and excess material at the contact points is trimmed. The object should then be immersed in a substance that dissolves any uncured resin residue. Isopropyl alcohol (propan-2-ol, C3H7OH) is one of the most popular solvents for this purpose. However, new types of resins that are soluble in water are also becoming available.

Additionally, the object can be freely sanded, polished, painted, or subjected to other surface treatment. The finished element is exposed to ultraviolet radiation, which is sourced from sunlight. Therefore, it can also be additionally exposed to UV radiation to harden the object and protect it from potential damage caused by natural light. Studies show that samples subjected to additional irradiation exhibit significantly better mechanical properties, higher tensile strength, hardness, and temperature resistance [7]. Figure 3 shows an example of an object subjected to polishing. As can be seen on the left side, it is matte with visible traces of supports. Then, the following stages of the process are shown until it finally achieves full transparency. Additionally, the object is coated with acrylic lacquer for additional protection against natural UV radiation.

Fig. 3. Example of finishing treatment – polishing [3]

1.3. Typical drawbacks of incremental manufacturing

According to Aranda [8], in the case of incremental manufacturing, as well as other technologies, the produced element may be subject to certain drawbacks. These can relate to the model, triangulation mesh, production process, or the object itself. Depending on the type of technology, different types of defects may occur.

In the case of stereolithography, one of the most common problems is warping of the element. This is a deformation caused by uneven solidification of the surface of the newly created object under the influence of sunlight. This happens when one side is more exposed to natural UV radiation than the others. This causes the area to solidify, creating stress and therefore shrinkage. This problem is particularly noticeable in long, flat objects, and affects them the most.

Another important defect is the so-called delamination of the element. During the layering process, the layers do not bond properly, resulting in either gaps or joining at a specific point to form a group of unconnected sheets or gaps. The most common cause of this problem is a lack of proper support, issues with the UV radiation generation system, or low-quality resin.

The first two types of defects directly affect the physical element, but some defects may be caused by an improperly created model or G-code. According to Aranda [8], there are seven typical errors related to the model and STL file:

- Incorrectly set triangle normals – a file conversion issue that causes the inner edge of the triangle to be interpreted as the outer edge.
- Gaps in the model – typically occur at the junction of two edges with complex geometry.
- Noise shell – errors in the form of additional small elements consisting of only a few triangles.
- Overlapping triangles – several triangles are located in exactly the same position.
- Intersecting triangles – similar to the previous defect, caused by differences in the angle of the triangle and its position.
- Incorrect edges – errors in the arrangement of the edges of the object's geometry.
- Shells – a problem related to complex elements, where additional parts may be created during conversion, or some parts may be absorbed by the model.

1.4. Scanning in production engineering

Spatial scanning finds its most important application in production engineering in reverse engineering, product and supply quality control, tool optimization, and manufacturing of precise elements. The latter example is particularly important in the design and production of custom-made products such as prostheses. In quality control, scanning allows for the comparison of the real object with the computer model, enabling the worker to immediately check whether the manufactured product meets the specified requirements. In more advanced cases, it is possible to perform an analysis of damage to significant elements of the product [9].

Methods of spatial scanning are divided into two main groups: contact and non-contact. The first one involves the use of a sensor that creates a digital model of the object by physical contact with it. Non-contact methods are based on various types of radiation, including laser and visible light. Beams pass through or reflect off the object and the appropriate sensors analyze their properties.

3D scanning using a laser beam is carried out using two types of stationary and handheld devices. In both cases, the coordinates of the points are obtained from the surface of the object being scanned according to the principle of triangulation. Laser beams are directed onto the object, causing deformation on its surface geometry. Their image is recorded by two sensors such as cameras. This creates a triangle, with one vertex being the laser and the other two sensors forming a line between them. Each of them measures the angle relevant to it, and the coordinates are calculated based on geometric relationships. Figure 4 illustrates this process. Although this technology may seem complicated, it is actually a simple process based on mathematical principles [10].

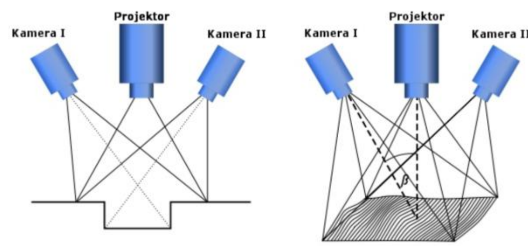

Fig. 4. Scanning using two cameras and a projector [10]

When performing this type of measurement, one extremely important fact must be taken into account. The object cannot reflect the laser beam in an uncontrolled manner. Its surface must be matte. If the object is too reflective, it can be covered with a layer of anti-reflective substance. Usually, it is available in pressure containers, which allow it to be sprayed onto the surface of the object, and after some time, it evaporates on its own. Another drawback of this technology is the problem of measuring elements to which the three previously described elements do not have simultaneous access. Typically, these are gaps or recesses with a very large ratio of height to base width.

The result of scanning is an accurate image of the object. It can be presented in a two-dimensional form. This is useful for flat elements or when only a fragment of the object is important, such as the interior. Another way to represent the scan in a two-dimensional form is a photoplan. The point cloud is converted into a 2D image. This is mainly used for documenting large objects, such as buildings. In the technique, three-dimensional models and point clouds are commonly used. This approach allows for a full analysis of the element, determining its exact dimensions, identifying individual components, and more [11].

2. MATERIALS AND METHODS

2.1. Specimen preparation - 3D Printer

The elements subjected to the study will be produced on the "Orange 10" device manufactured by Longer 3d, presented in Figure 5. This is a low-budget 3D printer designed mainly for the production of individual elements. Detailed technical data are presented in Table 1.

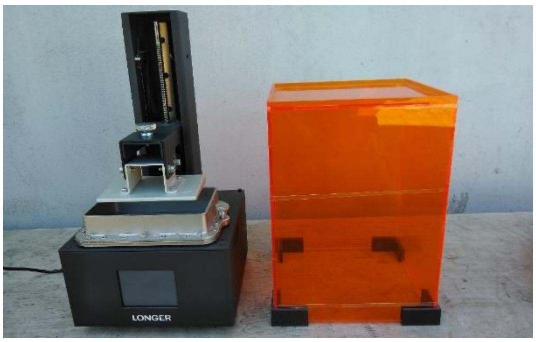

Fig. 5. Longer 3D Orange 10 SLA printer used to prepare samples

Tab. 1. Technical parameters of Orange 10 printer [12]

Technology	LCD stereolithography
Working space size	98 x 55 x 140 mm
Layer thickness	0.01-0.10 mm
Z-axis accuracy	10 µm
Printing speed	30 mm/h at 100 µm layer thickness
Material	Photopolymer resin
UV radiation source	UV LED 405 nm
Dimensions	6.7" x 6.7" x 14.2" (170 x 170 x 360 mm)
Total weight	7.0 kg
Power requirements	100-240 V AC, 50/60 Hz
Power consumption	60 W
Technology	LCD stereolithography

2.2. Materials used

As a material for making samples, Nova3D resin was used, which is characterized by high tensile strength and low shrinkage. It features clear, full-color prints after curing. Table 2 shows the specifications of the selected resin. The most important parameter when choosing the appropriate filament for the device is the curing wavelength. This value for both the device and the photopolymer must be identical or at least match.

Tab. 2. Characteristics of used resin

Manufacturer	Nova3D
Color	Gray
Capacity	1 l
Weight	1.05 kg
Hardness	~85 D
Tensile strength	~68 MPa
Elongation at break	~10 %
Thermal deformation temperature	80°
Wavelength of curing	395-415 nm
Liquid density	1,05 g/cm³
Solid density	1,2 g/cm³
Curing time	2-30 s

2.3. Measuring equipment

HSCAN 300 Handheld 3D is a handheld scanner, operated directly by the operator. The process of scanning an object began with preparing the workspace. Reference points were prepared on a flat surface, creating a field on which the task was carried out. At the same time, each scanned object was covered with an anti-reflective coating. This was done using a commonly available spray that created a matte layer on the surface, which evaporated after a few tens of minutes. The element prepared in this way was placed in the field created by the previously applied points. Figure 6 shows a photo of the described process.

Fig. 6. Handheld scanner and measuring station

One can notice all of the mentioned elements on it, the device on the left is the scanner, while in the center there is a field of points and the scanned element covered with an anti-reflective substance.

2.4. Specimen characteristics

The subject of the research are selected components of the gear transmission mechanism intended for the needs of the Modular Production System for Education. Its design was developed by employees of the Koszalin University of Technology directly involved in this project.

The worm gear consists of four main parts, including the lower and upper covers, the gear wheel, and the worm. It is a set of elements with complex shapes that differ from each other. Thanks to this diversity, measurements of non-repeating dimensions can be taken, which will allow for obtaining reliable results. Model of transmission is shown in Figure 7.

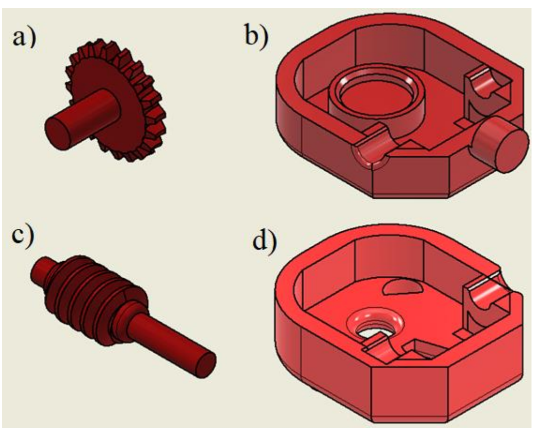

Fig. 7. Three-dimensional model of the examined element: a) gear wheel, b) lower cover, c) worm, d) upper cover [13]

2.5. Software used for analysis

The received model was analyzed in the "GOM Inspect" software. First, the obtained data had to be prepared. This process mainly involved filling in missing elements of the model. The scanning process is not perfect, and some parts of the object cannot be covered by it. This applies particularly to internal fragments and narrow areas where laser beam access is difficult. The program allows for "patching" such gaps by using the average of adjacent points. Although these are not actual values, the created surfaces effectively replace empty spaces. This enables later analysis of the object, and the method based on the local average value is commonly used.

2.6. Methodology

The selection of input parameters to be tested depends on one key element: the device on which the objects will be produced. The range of manipulation of individual parameters is significant, and it must be consistent with the capabilities of the 3D printer. It may also depend on the type and parameters of the material used, the capabilities of the software used, technological limitations, etc. For each of these factors, a strictly defined range of values has been specified for the tests.

In this case, there are three parameters, each with a significant range of manipulation. At the same time, all of them have an impact on the entire produced object. Some of the variable characteristics were omitted, despite the possibility of their change using the software. The reason for this decision is the fact that they concern only a negligible part of the entire object. In each tested case, there were supports between the object being tested and the platform, which were ultimately removed, so these values were omitted due to their lack of influence on the produced object.

There is another group of parameters that have some impact on the process. These are the values describing the geometry of the object. The more complex the produced element is, the more differences in external dimensions it has, especially protruding parts, the more difficult it is to create such an object using the technology and device used in this diploma thesis. However, the samples have already been set and their change is not possible, and therefore manipulation of this factor is also not possible. Another parameter, or rather a set of variables related to each other, is the positioning of the tested object on the work platform. Experimentally, one could study, for example, which angle of object positioning would be optimal, which place on the platform they should occupy, how the layers should be arranged. Such factors were omitted due to their high complexity and certain degree of subjectivity. These parameters might be too dependent on the operator, the resin used, and the device itself, which is not a high-end one in this case.

Another group of parameters could be factors related to the generation of supports. They are related to the shape of the object, variable values describing the bottom layers of the element, and directly to the geometry of the support itself. This description indicates that the role of these elements is quite significant since they are related to all variables that may affect the quality of the produced object, as well as those that concern the supports themselves. Therefore, to study this group of factors, an experiment would need to be planned, examining practically every parameter of additive manufacturing using stereolithography. Theoretically, this is possible, but the number of samples that would need to be produced would be enormous, resulting in high costs and time consumption.

Based on the arguments mentioned earlier, three parameters were selected which: according to literature, are the most important variables in this technology, relate only to the manufactured object, have a large range of manipulation with the applied device, and their significance emphasizes the strict relationships between them. Parameters related to the lower layers which are only part of the supports and those related to the arrangement and shape of the object were omitted. A detailed description of the selected parameters is provided at this point.

Layer thickness, $\overline{x}_1$ = w [μm] - this is the distance between the beginning and the end of a single layer that is produced during one cycle of the device. The smaller this parameter, the greater the reproduction of the prepared object. This value can take values in the range of 10 to 100 μm (w = 10 - 100 μm, minimum step 5 μm).

Curing time, $\overline{x}_2$= t_u [ms] – the time during which individual layers are exposed to UV radiation. Theoretically, this value can be any, but for this type of device, the range between 2000 and 15000 ms (t_u = 2000 - 15000 ms) is usually adopted, which is also consistent with the parameters of the applied resin. The general rule is that the thicker the layer, the longer the curing time. However, in some cases, mainly for small elements that must meet higher requirements for quality and durability, higher values of this parameter are used. However, this is associated with a longer time of manufacturing the entire object.

Lifting speed $\overline{x}_3$= s_p [mm/min] - the speed at which the platform moves along the Z-axis during normal range of motion. Increasing this parameter can to some extent shorten the time of object manufacturing. There is a possibility of this value affecting object delamination. This value must fall within the range of 10 to 600 mm/min (s_p = 10-600 mm/min).

Table 3 presents the matrix of the experimental design plan. It includes both the coded and actual values. The dimensions of the samples to be investigated will be selected. Those are the diameter of the circle in the gearbox housing and the diameter of the hole in the cylinder of the gearbox housing as indicated in Figure 8.

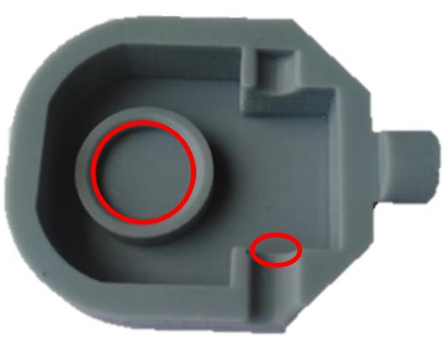

Fig. 8. Gearbox housing with marked dimensions subject to control

3. RESULTS AND DISCUSSION

The measured dimensions were located and their results are presented in Table 10. It contains real values as well as deviations of each element's dimensions. The largest deviation is -0.69 mm, while the smallest is -0.01 mm. Both of these values pertain to the second variable. In the case of the first dimension, the maximum and minimum deviations are smaller: -0.41 mm and -0.02 mm, respectively. No perfect results were obtained in either case. A cursory analysis reveals that the vast majority of deviations are negative, with only two dimensions being larger. This may be related to excessive resin shrinkage. This is a natural process, and in order to counteract it, changes in the dimensions should be introduced at the stage of object design.

For the examined case, with constants such as the properties of the resin and device parameters, such a value determined for the most optimal parameters would allow obtaining an error (according to preliminary estimates) of the order of one hundredth of a millimeter. However, it should be taken into account that this applies only to the first dimension, which is characterized by high predictability. It can be assumed that in the case of the second distance, the use of a correction coefficient based on the average may bring improvement, but it will not be as significant as in the first case. To confirm this, it would be necessary to conduct a study of the repeatability of results for optimal parameter configurations, and based on this, determine the aforementioned correction value. Table 4 presents the values of dimensions and their deviations from nominal values.

The analysis of the obtained results was carried out in the "Statistica" program [14]. The work started with creating a spreadsheet consisting of 5 columns and 16 rows. The number of columns results from the fact that 3 input parameters and two output factors were studied. The number of rows is the number of produced samples. According to the research plan, twenty sets of elements with different parameters should have been produced. However, four configurations of input factors made it impossible to produce any objects when they were applied to any extent. The measurement results were introduced only for the elements that were successfully produced.

Figures 9 to 14 show the dependency charts for each parameter based on the deviation. The "Statistica" software allows for the generation of any one or two-parameter chart. Graphic representation of the studied process allows for easier understanding of the problem and, as a result, its analysis, and determination of the most optimal combination of parameters.

Tab. 3. Five-level experimental plan for coded and real variables

	Experimental plan for coded variables			Experimental plan for real variables		
	$\breve{\bar{x}}_1 = \breve{\bar{w}}$	$\breve{\bar{x}}_2 = \breve{\bar{t}}_u$	$\breve{\bar{x}}_3 = \breve{\bar{s}}_p$	$\bar{w}$	$\bar{t_u}$	$\bar{s_p}$
No.	[-]	[-]	[-]	[μm]	[ms]	[mm/min]
1.	-	-	-	30	4635	130
2.	+	-	-	80	4635	130
3.	-	+	-	30	12365	130
4.	+	+	-	80	12365	130
5.	-	-	+	30	4635	480
6.	+	-	+	80	4635	480
7.	-	+	+	30	12365	480
8.	+	+	+	80	12365	480
9.	1.682	0	0	100	8500	310
10.	-1.682	0	0	10	8500	310
11.	0	1.682	0	55	15000	310
12.	0	-1.682	0	55	2000	310
13.	0	0	1.682	55	8500	600
14.	0	0	-1.682	55	8500	10
15.	0	0	0	55	8500	310
16.	0	0	0	55	8500	310
17.	0	0	0	55	8500	310
18.	0	0	0	55	8500	310
19.	0	0	0	55	8500	310
20.	0	0	0	55	8500	310

The graphs showing the deviation of the circle dimension can be found in figures 9-14. Analyzing the influence of the layer thickness and curing time (Fig. 9), it can be observed that the deviation decreases with the increase of both parameters. Relatively small values (up to -0.3 mm) are marked on the graph in dark red color. They form a range that covers the entire range of layer thickness, but depends on the curing time. The worst results of the circle dimension deviation were obtained for the largest layer thickness at the shortest curing time.

Figure 10 shows a graph of the dependence between layer thickness and lifting speed. The most optimal values are found in two areas. However, by increasing the permissible deviation from 0.2 to -0.2 mm, it can be observed that these values occur for the smallest and largest input variable values.

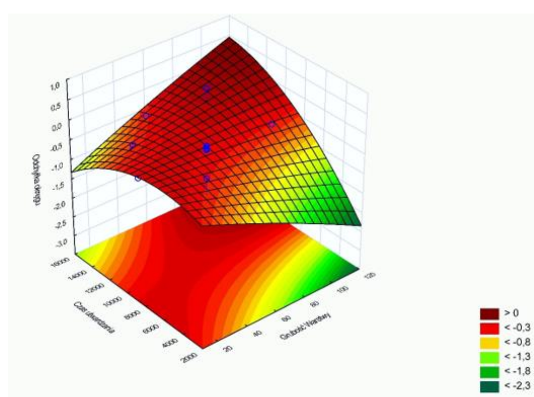

Fig. 9. Correlation chart: $\Delta y_1(w, t_u)$

Tab. 4. Values of dimensions and their deviations from the nominal value

	Layer Thickness	Curing time	Lift speed	Circle dimension	Circle deviation	Roll dimension	Roll deviation
No.	[μm]	[ms]	[mm/min]	[mm]	[mm]	[mm]	[mm]
1.	30	4635	130	15.48	-0.02	6.32	+0.12
2.	80	4635	130	-	-	-	-
3.	30	12365	130	14.93	-0.53	6.53	+0.33
4.	80	12365	130	15.09	-0.41	5.74	-0.46
5.	30	4635	480	-	-	-	-
6.	80	4635	480	-	-	-	-
7.	30	12365	480	15.11	-0.39	6.16	-0.04
8.	80	12365	480	15.75	0.25	5.51	-0.69
9.	100	8500	310	15.09	-0.41	5.76	-0.44
10.	10	8500	310	15.21	-0.29	5.87	-0.33
11.	55	15000	310	15.05	-0.45	5.99	-0.21
12.	55	2000	310	-	-	-	-
13.	55	8500	600	15.15	-0.35	6.13	-0.07
14.	55	8500	10	15.21	-0.29	6.16	-0.04
15.	55	8500	310	15.27	-0.23	6.07	-0.13
16.	55	8500	310	15.25	-0.25	5.98	-0.22
17.	55	8500	310	15.20	-0.30	6.13	-0.07
18.	55	8500	310	15.17	-0.33	6.19	-0.01
19.	55	8500	310	15.16	-0.34	5.88	-0.32
20.	55	8500	310	15.18	-0.32	5.84	-0.36

The least favorable dimensional deviation appears for the largest layer thickness in relation to the lifting speed, and also in the reverse case. The graph allows one to see a certain linear relationship, but the area in which the most favorable values occur is quite significant. This shows that there is little correlation between the input parameters.

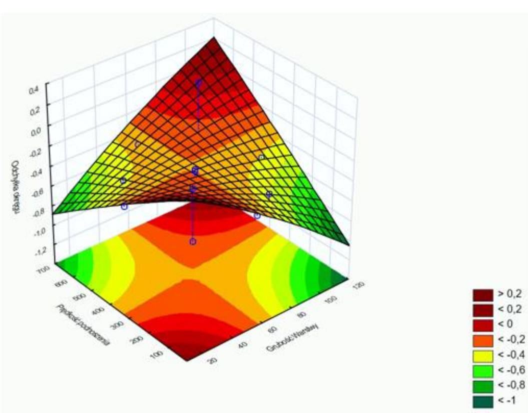

Fig. 10. Correlation chart: $\Delta y_1(w, s_p)$

Figure 11 shows a plot of the last two dependencies on the dimensional deviation for the circle: curing time and lifting speed. The smallest deviation values relate to the highest values of the output variables. However, assuming a certain tolerance, it can be seen that then the analyzed area will be decisively influenced by the curing time. The lifting speed, on the other hand, is less important. but not insignificant for the deviation value.

Summarizing the three charts. it can be concluded that the key mark for the process studied is the curing time. This parameter, in combination with the others. determined the value of the dimensional deviation in both cases. The relationship $\Delta y1(w,tu)$ is the most prominent, and it can be concluded from analysis of the graphs that it has the greatest influence on the process. On the other hand, the influence of layer thickness and lifting speed, has some noticeable correlation. However, this is the least important correlation because the field of optimal values is located in a large area, while the smallest deviation occurs in two separate fields.

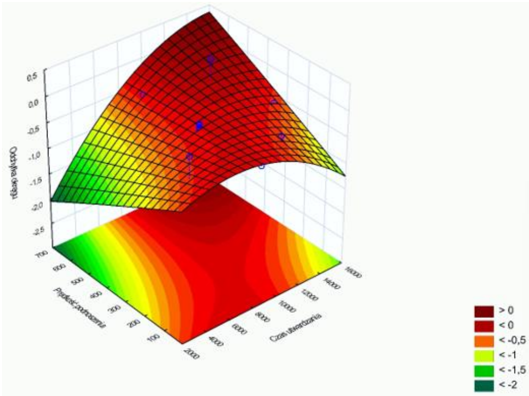

Fig. 11. Correlation chart: $\Delta y_1(t_u, s_p)$

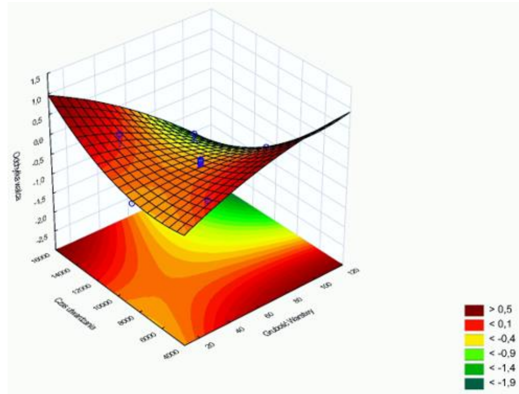

Fig. 12. Correlation chart: $\Delta y_2(w, t_u)$

Three dependency plots were prepared for the second output variable as well. Figure 12 shows an analysis of the effect of film thickness and curing time. You can see the complex relationship between these parameters. The field has taken the shape of a cross, so for narrow values of one parameter corresponds to the entire range of values of the other. which applies to curing time as well as film thickness. The largest deviation values appear at the maximum values of both input variables. The smallest in the reverse case: layer thickness 15 - 40 µm, curing time 4000-1000 ms.

Figure 13 shows a graph of the relationship between layer thickness and lifting speed. The most optimal values just as in the case of the dimensional deviation for the circle are in two areas. If a larger range of this parameter is given to the analysis. the relationship between layer thickness and lifting speed is still difficult to determine. It can be concluded that the least favorable dimensional deviation is formed for the highest values of layer thickness, but the second parameter in this case covers almost the entire range studied.

The last graph of the relationship for the roller deviation is in Figure 14, which shows the effect of curing time and lifting speed. The relationship of these parameters is significantly different from the previously analyzed cases.

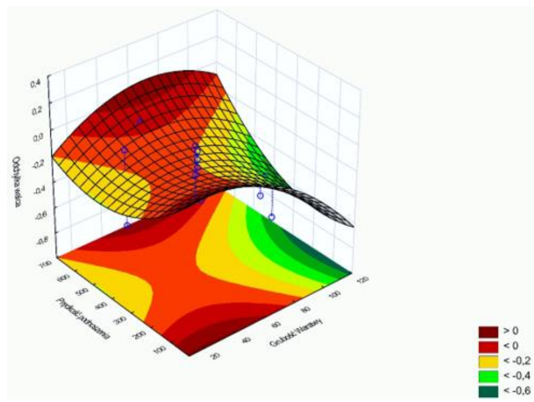

Fig. 13. Correlation chart: $\Delta y_2(w, s_p)$

However, based on this graph, it can be concluded that the smallest deviations do not depend on the lifting speed since the most favorable values appear to you over the entire range of this input variable. As for the curing time, it is possible to determine a range of values which are characterized by relatively small deviations. However, it is a rather large range starting at 4000 ms and ending at least at 16000 ms.

Analysis of the graphs of the dependence of the dimensional deviation for the roller brings less clear conclusions. As in the first case, the decisive influence is the curing time and the relationship of this parameter to the thickness of the layer. However, the fields over which the most favorable deviation values occur are quite large. Therefore, the influence of input parameters cannot be predicted precisely, although it is possible to some extent.

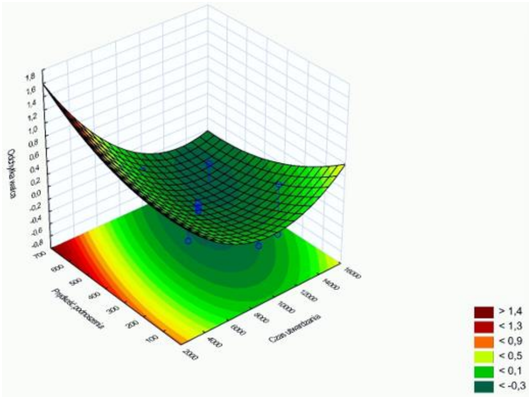

Fig. 14. Correlation chart: $\Delta y_2(t_u, s_p)$

In addition, chart analysis confirms the correctness of these data. The optimal values of the dimensional deviation for the circle take the form: film thickness: 47.822 µm, curing time: 9501.696 µs, lift speed: 268.608 m/s. The dimensional deviation for the cylinder is characterized by the following values: film thickness: 31.442 µm, curing time: 9603.336 µs, lifting speed: 453.648 m/s. Analyzing these results. it can be seen that the optimal curing time for both cases is very similar. Some similarity can also be seen in the case of layer thickness. Despite some difference, both values are less than the central value. The lifting speed has the most impact on the process.

4. CONCLUSIONS

Tests were conducted using three input parameters: curing time, film thickness, and lift speed. Their results were two output variables called deviations. Two different diameters were measured, followed by an analysis of the results obtained. The chapter yielded the following observations and conclusions.

1. Several test subjects were made. in order to select the place on the platform and the parameters of the supports.
2. The configuration of parameters number 2, 5, 6 and 12 prevented the production of elements.
3. Manufactured components differ from their computer models. are subject to defects that degrade their performance values.
4. Most of the measured deviations are negative. the smallest being -0.01 mm, the largest 0.69 mm.
5. The optimum values of dimensional deviation for the circle take the form: film thickness: 47.822 µm, curing time: 9501.696 µs, lift speed: 268.608 m/s.
6. The dimensional deviation for the roll is characterized by the following optimal values: film thickness: 31.442 µm, curing time: 9603.336 µs, lift speed: 453.648 m/s.
7. The key parameter for the course of the process studied is the curing time, the second is the thickness of the layer, while the least important factor is the lifting speed.

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