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# IMPROVED APPROACH TO DESIGNING THE VACUUM CHANNELS FOR ADDITIVELY MANUFACTURED THERMOFORMING MOULDS

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***Abstract:*** *One of the significant characteristic elements of a vacuum thermoforming mould is the vacuum channels which traditionally are small diameter holes drilled through the mould body. The proper diameter of the vacuum hole should not exceed the thickness of the sheet that covers it. If the vacuum hole is too large, the sheet will thermoform into it and cause the appearance of marks or rupture as it draws. This paper proposes a practical framework for custom-designing efficient vacuum holes in thermoforming moulds through a systematic approach. By changing the inclination of vacuum channels and printing parameters, smaller diameter holes of 0.35 mm have been obtained. The significant advantage of using additive technologies is the freedom in design, fabrication of complex holes or hollow geometries in the same process, and saving of material.*

***Key words:*** *vacuum thermoforming, Fused Filament Fabrication, additive manufacturing, vacuum channels, vacuum holes, thermoforming mould.*

## 1. INTRODUCTION

The earliest plastics applications were performed by simply heating, bending, and cooling a plastic sheet over a particular product or mould. Later, between 1936 and 1940, this process was called thermoforming, and the first vacuum thermoforming equipment was patented [1]. The steps of modelling a plastic sheet using this technology will remain similar for modern equipment.

As the name suggests, the vacuum forming process relies on a vacuum system. When air suction is applied, the heated plastic sheet will draw around the mould to create the desired shape. Consequently, vacuum holes (vacuum channels or vent holes) are the characteristic elements of such moulds. Traditionally, small holes are drilled through the mould body, and as a rule of thumb, the diameter of the vacuum hole should not exceed the thickness of the stretched heated sheet that covers it [2]. Otherwise, there is a risk of marks and signs to appear (nibs or nipples), and in some situations, the heated foil can thin out to the point of rupture.

Commonly, the smallest used diameter holes that can be obtained through drilling, electrical discharge machining (EDM) or carbon dioxide lasers are 0.34 mm (#80 or 0.0135 in), 0.3 mm (0.012 in) and 10 microns, respectively [2,3]. In his book [4], Stanley R. Rosen describes the 0.5 mm (#76 or 0.02 in) as the minimum practical drill size used on a standard drill press. Companies also make other recommendations, for example, Amtek Company, Inc. suggests a maximum hole diameter of 0.75 mm for foils with a thickness lower than 1 mm and 1 mm diameter for foils up to 2 mm in thickness [5]. Stephen Webster Plastic Company [6] recommends a vacuum hole diameter of 0.25 mm for sheet gauges smaller than 1.5 mm and 0.8 mm and 1.5 mm in hole diameter for foils smaller than 6 mm.

The major advantage of using additive technologies is the freedom in design and mould production with minimal material waste. This approach also allows obtaining the vent holes in the same process as mould fabrication (which will eliminate the need for post-processing).

In the specialized literature, a few studies present the possibility and advantages of obtaining a thermoforming mould, using additive manufacturing, in which the focus is on the comparison of cooling or air extraction channels compared to the channels obtained in the case of moulds manufactured by classical technologies (turning, milling, drilling, forging).

Chaolin T. et al. recommend in their paper the implementation of support structures inside the cooling channels of an injection mould, obtained by LBF technology (Laser Powder Bed Fusion). Such structures improve manufacturability and eliminate some geometric constraints of LPBF technology by suppressing the collapse and warpage of the overhang structures inside the channels [7]. Mazur et al. describe two approaches that aim to improve or eliminate the processing uncertainties associated with the cooling channels in an injection mould, manufactured through SLM technology (Selective Laser Melting) and H13 steel [8]. Similar to the previous paper, it is proposed to use lattice support structures inside the channels and a new self-supporting cross section ("tear-drop"). Both approaches reduce channel surface roughness and increase dimensional accuracy at the detriment of circular cross-section cooling channels.

Due to the brief information in the literature, the technologies considered in this paper are vacuum forming as a thermoforming process and Fused Filament Fabrication (FFF) as an additive tool manufacturing technology. The lattice support structure approach cannot be considered in this case due to the small diameters of the air extraction channels (less than 1.5 mm), but it can be used for further fabrication of cooling channels. Consequently, the “tear-drop” profile will be used as a second channel cross-section alongside the classic circular cross-section.

This paper proposes a practical framework for customizing efficient vacuum holes through a systematic approach and an adequate statistical Design of Experiments plan. The main goal was to obtain a thermoform mold using affordable 3D printing desktop equipment and dedicated materials to sustain the requirement for both technologies involved. Furthermore, different inner shapes, diameters, and arrangements of the vacuum channels can be used. This approach will not leave marks on the finished thermoformed product and will improve the airflow.

## 2. EXPERIMENTAL WORK

### 2.1. Material and equipment

The used materials and equipment were considered based on the inherent aspects of the manufacturing process (additive manufacturing technology and thermoforming).

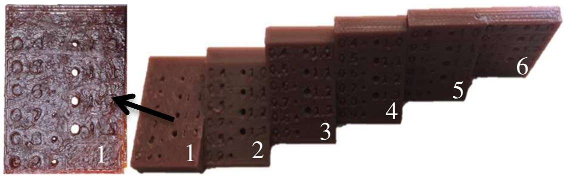
For manufacturing the studied sample and the preliminary experiments, the 3D printer Ultimaker 3 and PLA material from BASF Company were used.

Ultimaker 3 was used because it is a professional, robust desktop 3D printer that meets all the requirements for experimental tests (printing volume, dimensional accuracy, etc.) and, at the same time, offers the possibility to use high-performance materials (nozzle temperature up to 300 °C). PLA material was considered because of its affordability, ease of printing (it allows high printing speeds and low nozzle and bed temperatures), thus being universal (it can be used on any 3D printer dedicated to FFF manufacturing). Previous research on cooling a thermoforming mould [9] showed that the PLA material and Voronoi CC cooling channels pattern offers the best result in terms of cooling efficiency and mass reduction of the mould.

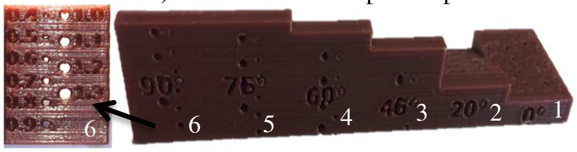
Considered elements to be studied, vacuum hole diameter and area, were measured using the digital microscope Keyence VHX 700, followed by a statistical interpretation of the results in Microsoft Excel, using the multiple linear regression method.

### 2.2. Preliminary test

The motivation for this paper comes from an initial test that consists of 6 rectangular parallelepipeds with 10 holes/channels, each of different diameters. Besides the channel diameter between 0.4 mm and 1.3 mm, another important feature of the sample from Figure 1, is the orientation of each parallelepiped (geometry) during the 3D-FFF printing. Different angles indicated on the back side of the printed part (Figure 1. b) referred to the inclination of the top surface of each section to the build plate.



a) Front side of the printed part



b) Back side of the printed part.

**Fig. 1.** Preliminary printed sample with different angles.

According to the initial tests, the smallest protruded hole, for all 6 orientations, corresponds to the value of 0.8 mm diameter (value inscribed on the front side of the printed part). The smallest pierced hole has a diameter of 0.4 mm (in CAD) and was obtained in sample 6. The 0.7 mm hole is clogged in the case of sample 1 (corresponding to the 0° inclination angle) and has a measured value of 0.28 mm, corresponding to the second sample, respectively 0.43 mm, for the third sample.

From the initial test, it can be concluded that the real value (further referred to as measured value) of the obtained diameter depends on the orientation of the parallelepipeds and the nominal diameter of the hole. Other influencing factors of the shape and dimensional precision of the channels obtained by FFF additive manufacturing are the material properties (viscosity, melt flow, melting temperature, shrinkage rate, etc.), printing properties (printing speed and temperature, retraction and coasting settings, layer height, printing orientation, etc.) and mechanical or operational issues (inadequate layer calibration, un-calibrated feeding mechanism, improperly lubricated axles, etc. ).

The layer of extruded molten material is forcibly cooled by convection systems (cooling employing fans with directed airflow in the working area), leading to an inevitable volumetric shrinkage. Yaman [10] propose an approach where shrinkage is utilized to eliminate the effects of shrinkage by using stretching lines placed over the perimeters of the holes. Support structures or self-supporting designs of the channels are recommended to avoid dimensional and geometrical inaccuracies resulting during the heating and cooling of the recent deposit layer.

### 2.3. Experimental study

A mixed-level L16 ($2^3$), ($4^4$) Taguchi design was used to determine the influence of the main input factors on the vacuum channels (air extraction hole) diameter and cross-sectional area. The advantage of this approach is that it allows studying the influence of 7 input factors with only 16 runs and that 4 factors, considered the most important, will be varied 4 times, and the other 3 will have only 2 levels of variation. The Analysis of Variance (ANOVA) method was used to perform a numerical and statistical evaluation of the measure in which a process input parameter influences the two chosen output factors. Also, ANOVA was used to analyze the implication of the explanatory variables, the interactions in the response variable, and if the obtained regression model is statistically significant.

Thus, in this research concerning the manufacture of vacuum channels, the factors presented in Table 1 were considered.

*Table 1.*

**L16 ($2^3$), ($4^4$) Taguchi design for the current application.**

| Runs | Hole diameter [mm] | Tilt angle [°] | Printing speed [mm/s] | Printing temperature [°C] | Section shape | Layer height [mm] | Hole horizontal expansion [mm] |
|---|---|---|---|---|---|---|---|
| L1 | 0.4 | 0 | 25 | 190 | C | 0.1 | 0 |
| L2 | 0.4 | 30 | 30 | 195 | C | 0.2 | 0.2 |
| L3 | 0.4 | 60 | 35 | 200 | T | 0.1 | 0.2 |
| L4 | 0.4 | 90 | 40 | 205 | T | 0.2 | 0 |
| L5 | 0.6 | 0 | 30 | 200 | T | 0.2 | 0 |
| L6 | 0.6 | 30 | 25 | 205 | T | 0.1 | 0.2 |
| L7 | 0.6 | 60 | 40 | 190 | C | 0.2 | 0.2 |
| L8 | 0.6 | 90 | 35 | 195 | C | 0.1 | 0 |
| L9 | 0.8 | 0 | 35 | 205 | C | 0.2 | 0.2 |
| L10 | 0.8 | 30 | 40 | 200 | C | 0.1 | 0 |
| L11 | 0.8 | 60 | 25 | 195 | T | 0.2 | 0 |
| L12 | 0.8 | 90 | 30 | 190 | T | 0.1 | 0.2 |
| L13 | 1.0 | 0 | 40 | 195 | T | 0.1 | 0.2 |
| L14 | 1.0 | 30 | 35 | 190 | T | 0.2 | 0 |
| L15 | 1.0 | 60 | 30 | 205 | C | 0.1 | 0 |
| L16 | 1.0 | 90 | 25 | 200 | C | 0.2 | 0.2 |

For the experimental study, a ⌀29x20 [mm] cylinder was used as a base, and 15 channels (Figure 2) were made, according to the indications in Table 1.

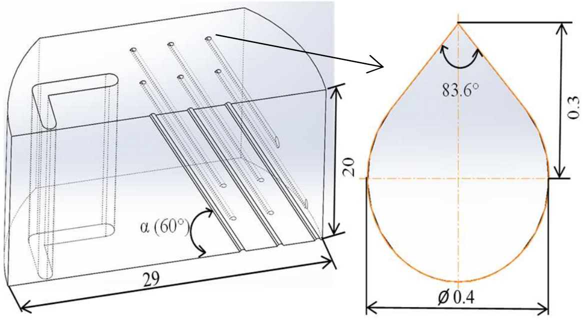


**Fig. 2.** Virtual model of the samples.

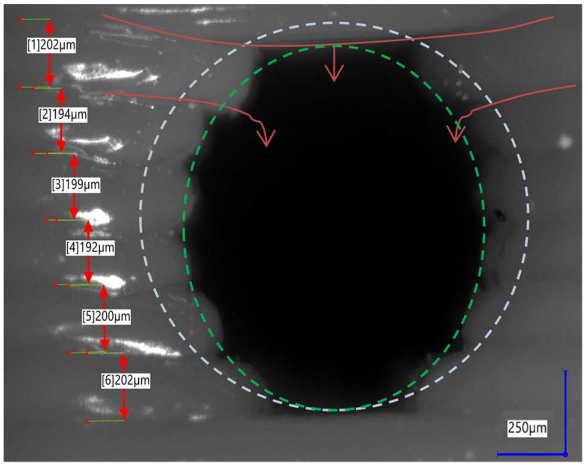
Tilt inclination [°] refers to the angle α (Figure 2) between the printing bed and the axis of symmetry of the vacuum channels. For 90° tilt angle, the holes were printed perpendicular on the build platform. The printing speeds [mm/s] of the top and bottom surfaces and the inner and outer walls are identical to facilitate the analysis of the results and reduce the number of input parameters associated with FFF additive manufacturing.

Suppose the printing speed proves to be a factor with a high impact on the studied output factors. In that case, a new Taguchi design can be done in which the four printing process parameters associated with speed are taken into account individually. The chosen printing temperatures [°C] are based on the minimum and maximum values offered by the material manufacturer.

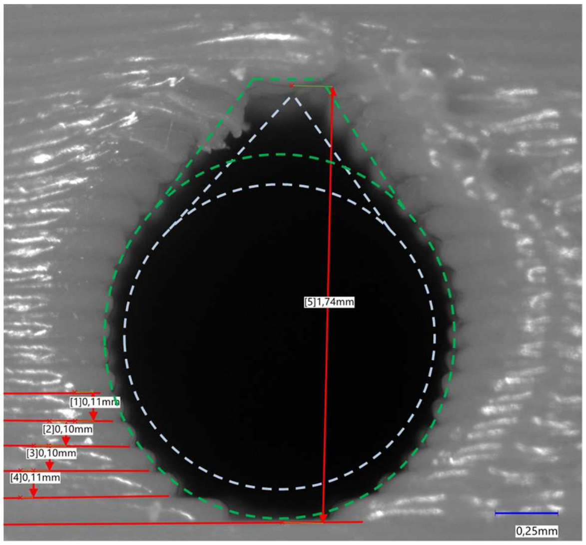
"C" Section shape (Figure 3. a) refers to the circular cross-section of the vacuum channel, while the "T" refers to a "tear-drop shape", also known as a self-supporting structure. This last approach, presented in (Figure 3. b), allows channels with circular cross-sections to be printed more precisely.

During the deposition of multiple layers of molten material, in the attempt to form the vacuum channels, the temperature gradient mechanism [7] will lead to problems such as warpage and/or collapse of the structure (accordingly to Figure. 3, represented red line and arrow).

The value indicated in square brackets ([1] to [6] Figure 3. a) and [1] to [4] Fig 3. b) represents the measured Layer height which corresponds with the value from Table 1. In both figures, the white dashed line defines the theoretical shape of the vacuum channel, while the green dashed profile represents the obtained one.



a) "C" shape hole from L9 sample

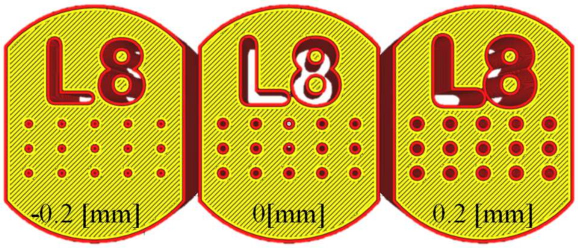


b) "T" shape hole from L13 sample

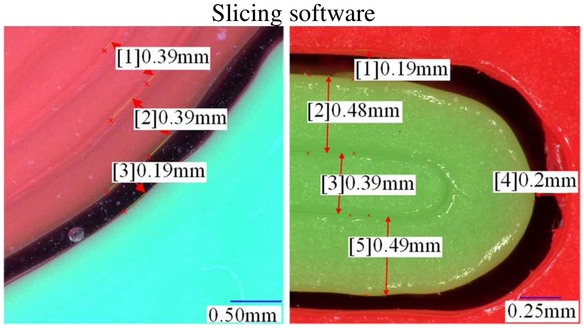
**Fig. 3.** Different section shapes of the printed sample.

Hole horizontal expansion is part of the "Wall" print settings group in Ultimaker Cura Slicer and is available in Expert Mode or by adding it manually.

These settings affect only the vertical holes and allow for reducing or increasing their dimensions (Figure 4. a). Since the hole is considered a continuous open profile/volume from the top to the bottom surface of the part, the overall dimensions of the printed samples, Layer Thickness (Lt), and extruded or cut-out profiles remain untouched (Figure 4 b).



a) ±0.2 mm Hole Horizontal Expansion effect in Cura Slicing software



b) 0.2 mm Hole Horizontal Expansion effect on the printed part

**Fig. 4.** Different effects of the hole horizontal expansion print setting.

The diameter and area of each of the 15 channels obtained for all 16 runs were analyzed using a digital microscope, according to Figure 5. When printing a line of plastic in a curve motion or when a stop or a change of direction is required, the melted plastic tends to get dragged along with the nozzle in the hole, resulting in the unique shapes of each sample.

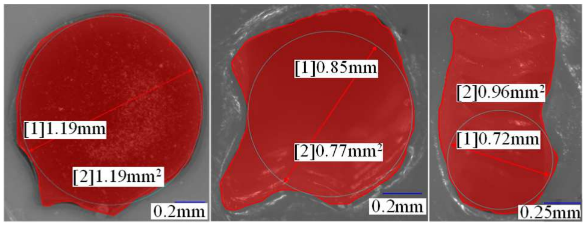


**Fig. 5.** Determination of the values of diameters and areas obtained after printing for different types of samples.

## 3. RESULTS AND ANALYSIS OF DATA

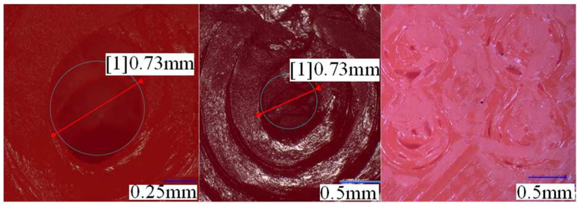
To simplify the further analysis, average of the measured area and the average of the measured diameters of the holes are used. All the obtained data can be seen in Table 2 alongside the values for each sample's specific deviation. It must be mentioned that no tolerance field was imposed in the data analysis due to the lack of a normative dedicated to additive manufacturing and shape or dimensional deviations.

*Table 2.*

**The results obtained after the tests.**

| Runs | Average of measured areas [mm²] | Nominal Area of section hole [mm²] | Deviation of measured area [mm²] | Average of measured diam. [mm] | Nominal Hole diameter [mm] | Deviation of measured diam. [mm] |
|---|---|---|---|---|---|---|
| L1 | 0.121 | 0.126 | -0.005 | 0.36 | 0.4 | -0.04 |
| L2 | 0 | 0.252 | -0.252 | 0 | 0.4 | -0.40 |
| L3 | 1.079 | 0.158 | 0.921 | 0.53 | 0.4 | 0.13 |
| L4 | 0 | 0.137 | -0.137 | 0.00 | 0.4 | -0.40 |
| L5 | 0.844 | 0.308 | 0.536 | 0.53 | 0.6 | -0.07 |
| L6 | 1.179 | 0.615 | 0.564 | 0.83 | 0.6 | 0.23 |
| L7 | 0.681 | 0.326 | 0.355 | 0.84 | 0.6 | 0.24 |
| L8 | 0.126 | 0.283 | -0.157 | 0.35 | 0.6 | -0.25 |
| L9 | 1.153 | 0.503 | 0.650 | 1.14 | 0.8 | 0.34 |
| L10 | 0.925 | 1.006 | -0.081 | 0.73 | 0.8 | -0.07 |
| L11 | 0.441 | 0.632 | -0.191 | 0.65 | 0.8 | -0.15 |
| L12 | 1.102 | 0.547 | 0.555 | 1.06 | 0.8 | 0.26 |
| L13 | 1.752 | 0.855 | 0.897 | 1.36 | 1.0 | 0.36 |
| L14 | 1.623 | 1.710 | -0.087 | 0.98 | 1.0 | -0.02 |
| L15 | 0.762 | 0.907 | -0.145 | 0.86 | 1.0 | -0.14 |
| L16 | 1.177 | 0.785 | 0.392 | 1.18 | 1.0 | 0.18 |

According to the data from the previous table, it can be seen that the channels with the smallest diameters were obtained in the case of samples L8 and L1 (0.35 mm and respectively 0.36 mm). In the case of the samples obtained with the corresponding parameters of the L2 and L4 run, both output factors have the value 0. In the case of these samples, from Figure 6, all vacuum channels were closed or clogged with materials, and the air could not pass through. As shown in Figure 6 a), on the top surface, holes can be seen, but due to the combination of input factors (especially 30° tilt angle and 0.2 mm layer height), obtaining a continuous hole is impossible along the entire length of the sample.



a) L2 sample b) L4 sample

**Fig. 6.** Clogged and closed vacuum channels.

A multiple linear regression method was used for a statistical interpretation and numerical quantification of the relationship between the 7 explanatory variables (independent variables) and the 2 chosen response variables (dependent variables). Following the mathematical approach to determine the influences of independent factors on the real/measured values of the diameters, it was obtained and presented in Table 3. The R-squared (Coefficient of determination) represents the percentage of the dependent variable variance [11,12]. A value of 0.892 indicates that 89.2% of the variation in the measured diameter can be explained by the independent variables (Nominal Hole diameter, Tilt angle, Printing speed, Section Shape, etc.). The standard error shows the precision of the regression analysis. The standard distance between the predicted (regression line) and observed values is 0.18 [mm].

*Table 3.*

**Regression analysis output for the diameter of the obtained channels.**

| *Regression Statistics* | |
|---|---|
| Multiple R | 0,9449 |
| R Square | 0,8928 |
| Adjusted R Square | 0,7990 |
| Standard Error | 0,1797 |
| Observations | 16,0000 |

| **ANOVA** | | | | |
|---|---|---|---|---|
| | *df* | *SS* | *MS* | *F* |
| Regression | 7,0000 | 2,1510 | 0,3073 | 9,5194 |
| Residual | 8,0000 | 0,2582 | 0,0323 | ***Significance F*** |
| Total | 15,0000 | 2,4092 | | 0,0025 |

| | *Coefficients* | *Standard Error* | *t Stat* | *P-value* |
|---|---|---|---|---|
| Intercept | 0,3006 | 1,6230 | 0,1852 | 0,8577 |
| Hole diameter [mm] | 1,4387 | 0,2009 | 7,1621 | 0,0001 |
| Tilt angle [°] | -0,0017 | 0,0013 | -1,3064 | 0,2277 |
| Printing speed [mm/s] | 0,0015 | 0,0080 | 0,1889 | 0,8549 |
| Printing temperature [°C] | -0,0031 | 0,0080 | -0,3861 | 0,7095 |
| Section shape | 0,0633 | 0,0898 | 0,7045 | 0,5011 |
| Layer height [mm] | -0,9310 | 0,8983 | -1,0364 | 0,3303 |
| Hole horizontal expansion [mm] | 1,5480 | 0,4492 | 3,4465 | 0,0087 |

The most important output factor from the ANOVA analysis is the Significance F, also known as P-value for the F-test [12]. In this case, the 0.0025 value indicates that the regression model is statistically significant (<0.05 [11]). Since the results are reliable, the next step is to evaluate the P-values and Coefficients of each explanatory variable. In this case, 5 out of 7 independent variables are not statistically significant (P-value> 0.05), and for further tests, they can be removed and replaced with new input parameters. Besides the P-values, small Coefficients such as 0.0015 for Print speed, -0.0031 for Printing temperature, and -0.0017 for Tilt angle indicate low influence over the response variable. Both coefficients of hole diameter and Hhle horizontal expansion are positive, indicating that the measure hole diameter will also increase as both increases. For example, for each one-unit increase in Hole diameter (in CAD), the measured diameter is expected to increase by an average of 1.438 mm, also assuming the horizontal hole expansion, layer height, printing speed, etc. value remains constant.

Using the above-determined Coefficients, regression equation (1) can be created:

Measured diameter [mm] = 0,3 + 1,44*Hole diameter- 0,0017*Tilt angle + 0,0015*Print speed- 0,0031*Printing temp.+ 0,063 Section Shape- 0,93*Layer Height+ 1,55*Hole horizontal expansion (1)

The same steps are now used to investigate the influence of the same 7 explanatory variables over the average of the measured area (Table 4).

*Table 4.*

**Regression analysis output for the cross-section area of the obtained channels.**

| *Regression Statistics* | |
|---|---|
| Multiple R | 0,9311 |
| R Square | 0,8669 |
| Adjusted R Square | 0,7505 |
| Standard Error | 0,2741 |
| Observations | 16,0000 |

| **ANOVA** | | | | |
|---|---|---|---|---|
| | *df* | *SS* | *MS* | *F* |
| Regression | 7,0000 | 3,9176 | 0,5597 | 7,4467 |
| Residual | 8,0000 | 0,6012 | 0,0752 | ***Significance F*** |
| Total | 15,0000 | 4,5188 | | 0,0056 |

| | *Coefficients* | *Standard Error* | *t Stat* | *P-value* |
|---|---|---|---|---|
| Intercept | -1,1526 | 2,4764 | -0,4654 | 0,6540 |
| Hole diameter [mm] | 1,6415 | 0,3065 | 5,3556 | 0,0007 |
| Tilt angle [°] | -0,0043 | 0,0020 | -2,1058 | 0,0683 |
| Printing speed [mm/s] | 0,0130 | 0,0123 | 1,0593 | 0,3204 |
| Printing temperature [°C] | 0,0020 | 0,0123 | 0,1650 | 0,8730 |
| Section shape | 0,3843 | 0,1371 | 2,8033 | 0,0231 |
| Layer height [mm] | -1,4083 | 1,3707 | -1,0274 | 0,3343 |
| Hole horizontal expansion [mm] | 2,0500 | 0,6854 | 2,9911 | 0,0173 |

Again, the regression model is statistically significant due to the R-squared, standard error, and significance F values of 0.867; 0.274, and respectively 0.0056. For this study, only the P-values for Printing Speed, Printing temperature, Section Shape, and Layer height are bigger than 0.05.

Both hole diameter and horizontal expansion coefficients have the biggest positive values. With all the above data, regression equation (2) can be created:

Measured area [$mm^2$] = -1,15+ 1,64*Hole diameter- 0,0043*Tilt angle+ 0,012*Print speed+ 0,002*Printing temp.+ 0,38*Section Shape- 1,4*Layer Height+ 2,04*Hole horizontal expansion (2)

Both in the case of the measured values of the diameters and the area, it is not enough to strictly select the lowest numerical values because they are not an indicator of the printer's capabilities to accurate produce samples with the respective combinations of constructive and process parameters (selected at the beginning of the study). The diagram in Figure 7 gives an overview of the deviations from the nominal values obtained after 3D printing.

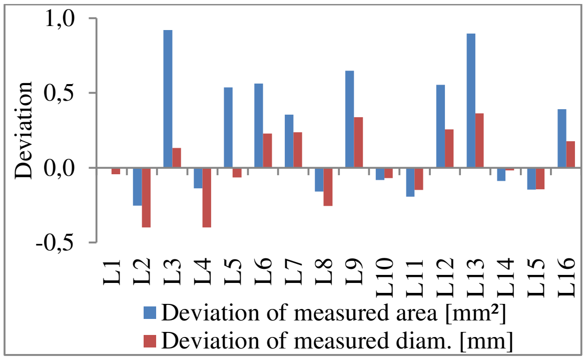


**Fig. 7.** Deviation value obtained after 3D printing.

A large positive value of the area deviation (as in the case of samples L3, L9, L13) indicates a higher risk of the appearance of deformations and irregularities on the surface of the thermoformed foil. The only common input parameter of those three samples is the value of 0.2 mm of Hole vertical expansion.

All the information resulting from the experimental and statistical can be accumulated in the plot in Figure 8.

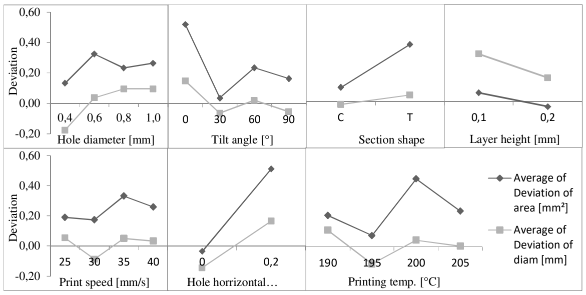


**Fig. 8.** Main effect plot for the average measured area and diameter of vacuum holes.

## 4. CONCLUSION

Based on the mixed-level L16 ($2^3$), (44) Taguchi design, the influence of 7 input factors over the vacuum channels diameter and cross-sectional area was determined using a small number of tests in the laboratory. Input parameters with the greatest influence on both output factors are Hole diameter and Hole horizontal expansion (printing parameters that will no longer be used in the following research).

The channels with the smallest diameters were obtained in the case of samples L8 and L1 (0.35 mm and respectively 0.36 mm), values which resemble the ones that can be obtained by using the drilling method. In addition to the smallest diameter, with the help of the combinations of factors that correspond to the L1 run, the most dimensionally and geometrically precise channels were obtained, resulting in minimal deviation values (0.005 [mm$^2$] for area and -0.04 [mm] for the diameter).

Regardless of whether the moulds are obtained through classic technologies or additives technologies, perpendicular holes/channels to the bottom surface of the mould are the most common. For future tests, input parameters specific to the L8 run will be considered due to the previously presented considerations.

The cooling system and vacuum channels for thermoforming plastic moulds obtained through FFF technology is still under development. Specific rules that define the design stage and the influencing factors of multiple independent variables over the response variables (mould temperature, cooling time, air extraction efficiency, foil surface quality, etc.) still do not exist.

The information accumulated during the experimental research and statistical analysis will be used in the improvement of the complex cooling and vacuum channels for the thermoforming moulds manufactured through additive manufacturing. Thus, for the following tests, the self-supporting shape section of the channel will be used at the expense of the circular shape and with different inclinations (not only perpendicular to the lower surface of the mould). This last approach and the FFF technology allow the realization of vacuum channels in 2-3 stages (with different diameters) or even connecting them in one channel.

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# ÎMBUNĂTĂȚIREA PROIECTĂRII CANALELOR DE VACUUM PENTRU MATRIȚELE DE TERMOFORMARE REALIZATE PRIN FABRICARE ADITIVĂ

Unul dintre elementele caracteristice ale unei matrițe de termoformare cu vacuum sunt canalele de vid care, în mod traditional, sunt găuri de diametru mic, obținute prin găurirea corpului matriței. Diametrul propriu-zis al găurii nu trebuie să depășească grosimea foliei termoformate. Pe masură ce aerul este extras din zona de lucru, dacă diametrul canalului de vid este prea mare, folia va fi absorbită, ducând astfel la apariția unor defecte sau chiar la ruperea foliei. Avantajul major al utilizării tehnologiilor de fabricare aditivă este libertatea de proiectare, economisirea de material și fabricarea de găuri complexe sau de structuri cave în cadrul aceluiași process. Printr-o abordare sistematică, această lucrare propune o alternative eficientă pentru crearea unor găuri de vid. Prin modificarea înclinației canalelor de vid și a parametrilor de printare 3D, s-au obținut canale pătrunse cu diametre mai mici de 0.35 mm.

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