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GENERATING MODELS FOR NUMERICAL STRENGTH TESTS OF 3D PRINTED ELEMENTS

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Abstract:
Additive manufacturing, or 3D printing, has become very common in professional applications in many industries. The 3D printing technology is especially suitable for making prototypes, demonstrators and small-batch production. The stiffness and strength of 3D prints depend on many factors, including among others infills, which are specific to this technology, as well as the orientation of the object during 3D printing. Where the stiffness or strength of an element is crucial, the only way is to empirically assess its properties. The advantage of 3D printing, i.e. incomplete infill of the interior of an object with the use of different types of infills (patterns) and different amounts of material, means that its mechanical properties differ from those of a solid element. The application of numerical tests, i.e. the finite element method (FEM), requires the creation of a 3D model while taking this infill into account. The modelling of elements for performing numerical strength calculations is time-consuming and labour-intensive. The article presents a proprietary original analytical method for generating various types of infills with varying infill density. The method was developed for typical infills (Grid, Triangular, Honeycomb). It was next implemented in the CAD environment using the iLogic tool of Autodesk Inventor. As a result, a tool for creating 3D models of objects consistent with those obtained from 3D printing was obtained. The method and tool were verified. Next, the influence of selected parameters of the 3D print on its mechanical properties was presented on three real objects. The results of numerical analyses revealed measurable benefits of such tests. The research conclusions also constitute recommendations for selecting the type and infill density of an object and its orientation in the printer with regard to the strength and stiffness obtained.

Key words: *3D printing, rapid prototyping, FEM tests, strength of 3D prints, numerical strength tests*

INTRODUCTION

The additive manufacturing technology, also referred to as 3D printing, has been developing dynamically for many years. Newer and newer solutions are being introduced, which allows for the use of various materials and enables obtaining more precise geometry transformation. At first, 3D printing as a new technology was used only for military and medical purposes due to the high cost of the devices. After the FDM (Fused Deposition Modelling) method was patented and popularized, 3D printers began to be used even at home for hobby purposes [1]. In the case of prototyping needs, the most frequently applied method is FDM, the great advantage of which is that it enables manipulating the density and type of infill (infill pattern), which allows for a significant reduction of 3D printing time and weight, and, in consequence, lower production costs. Due to the progress and accuracy of the 3D printing technology, it is applied to produce increasingly responsible elements used in industry and medicine. 3D prints often carry heavy loads, playing a key role in the operation of an entire set of elements. Due to the requirements regarding strength and stiffness that must be fulfilled by 3D prints, searches for methods of their determination are continued. In order to obtain an optimal print, it is necessary to take into account many factors, which ultimately translate into the mass (material consumption), 3D printing time and mechanical properties of the product. Empirical determination of the strength and stiffness of an element for various 3D printing parameters is a long and expensive process. The finite element method (FEM) is widely applied in mechanical engineering. However, to obtain reliable results, it is necessary to create a 3D model that, similarly to a 3D print, has a specific type and infill density. Such a model must be made anew each time, which is time-consuming and labour-intensive. Another problem is the lack of information on how to make a given type of infill to obtain the desired infill density. In such a situation, a needed tool is one that can automatically generate a specific type and infill density for the 3D printed model, while maintaining its external shape. The model obtained

in this way will allow FEM tests to be carried out so as to determine the influence of the type and infill density as well as the orientation of the object during 3D printing on its strength and stiffness.
The article presents the results of works the aim of which was to develop a method for generating infills and implement it as a tool in a CAD programme so that it is possible to perform FEM simulation on an object compatible with that obtained from a 3D printer. As a result, a 3D printouts model (3D print) generator was developed, which in the article is referred to as a generator for simplicity. The generator delivers input (3D model) for FEM tests.

LITERATURE REVIEW

Digital prototyping allows avoiding many errors at the design stage, i.e. before production costs are incurred [2, 3]. Constant development and popularization of the additive manufacturing technology means that elements made in this way carry out more and more responsible tasks and functions. These prints are no longer used only for prototyping purposes, but are becoming full-fledged and fully functional design elements, which places excessive demands on design engineers. It is important to select a proper material and 3D printing parameters in order to obtain a piece with correct geometry despite shrinkage [4, 5, 6, 7]. However, ensuring adequate mechanical strength and stiffness is gaining more and more importance. Initially, strength tests were carried out only in research laboratories associated with scientific and industrial institutes, where prints made of various materials were subjected to destructive testing [8, 9, 10]. Such tests, however, require a testing machine as well as time and costs to produce objects with various parameters, which are ultimately destroyed during the tests. Works aiming to increase durability and optimize 3D print parameters in terms of mechanical properties have been carried out in various centres [11, 12]. The influence of the filament itself and the method of its production on the durability of prints was also examined [13]. However, in the field of FEM analysis of 3D prints, there are only a few works, which address the problem in a selective way. In one of such works, the authors analysed the strength of samples made of plastic reinforced with carbon fibre [14]. In another, samples were tested and the results were compared with those obtained on a testing machine [15]. In one of the studies, the strength of supports was tested empirically and by the FEM method [16]. There are also works on specific objects, for example an FEM analysis of an electric motor with permanent magnets made with the use of 3D printing technology [17] or shifting numb of a gearbox made of steel by the SLM (Selective Laser Melting) method [18].
The available test results provide a lot of valuable information that allows selecting 3D printing parameters. However, these are general recommendations for simple standardized samples, which cannot be applied in the case of functional elements with complex shapes subjected to various loads.

METHODOLOGY OF RESEARCH

Creation of a method for generating infills required developing analytical theoretical foundations for each type of infill. Due to the variety of the types of infills, the most popular ones, used in nearly all printers, were selected for the works, i.e. Grid, Triangular and Honeycomb infills (Fig. 1).

Fig. 1 Types of infills selected for the generator (from the left: Grid, Triangular, HoneyComb)

Taking into account the parameters of FDM industrial printers, the nozzle diameter was assumed to be in the range of 0.2 mm ÷ 0.8 mm. For the selected types of infills, the infill density ranged from 10% to 90%. For such assumptions, parametric infill sketches dependant on the selected nozzle diameter and infill density were created Appropriate formulas were derived for each type of infill. Formulas allow for calculating the element size for each type of infill based on nozzle diameter and infill density The method and formulas were implemented into Autodesk Inventor Professional using the iLogic tool. The generator (3D printouts model generator), which was implemented by the iLogic method, created 3D models of a particular infill (Grid, Triangular, HoneyComb). Next, the generated models (3D models of infill) were validated by comparing them with the effects obtained from programs that generate a gcode for 3D printers (Simplify, UltiMaker Cura and PrusaSlicer) and by calculating the actual infill density. The proven tool was used to conduct numerical strength tests of three real elements.

FILL GENERATION METHOD

Appropriate diagrams for each type of infill were developed and the required mathematical relationships that make the infill geometry dependent on the nozzle diameter expressed in millimetres and on the infill density expressed as a percentage were derived. Fig. 2 shows stages of creating the final 3D model of 3D printout.
For each infill, the programme generates a sketch, which is next converted into a 3D model of the infill. The 3D object of the element is then converted to a shell. Three solids, i.e. the 3D object, the 3D object shell and the infill, form the final object, which is obtained with the use of the Boolean operation.
In the case of each infill, the pattern is created by a nozzle with a specific and defined diameter (ND) that is also the thickness of the 3D printed infill wall. For a given nozzle diameter, the size of the infill element is changed in order to obtain a pattern resulting from the infill density (ID).

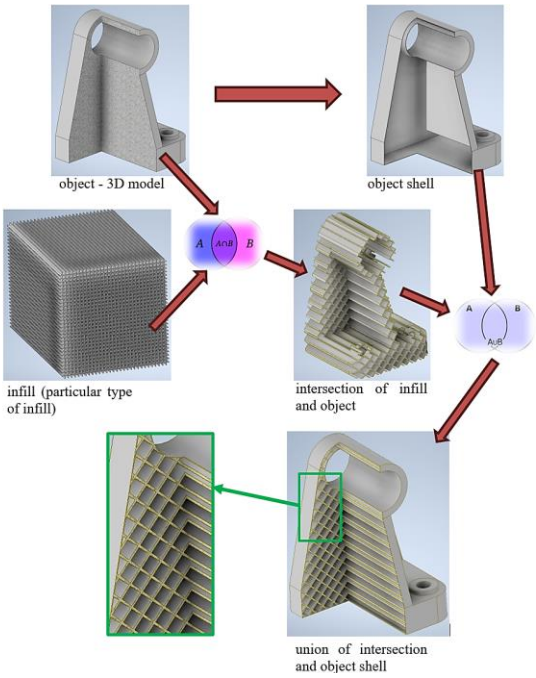

Fig. 2 Stages of creating the final object from the model, model shell and infill

The elements of selected infills are regular polygons. Elements are places without material (empty spaces). For the Grid infill, the element is a square with an SLG side (Fig. 3), for the Triangular infill, it is a triangle with an SLT side (Fig. 4), and for Honeycomb – a hexagon with an SLH side (Fig. 5).

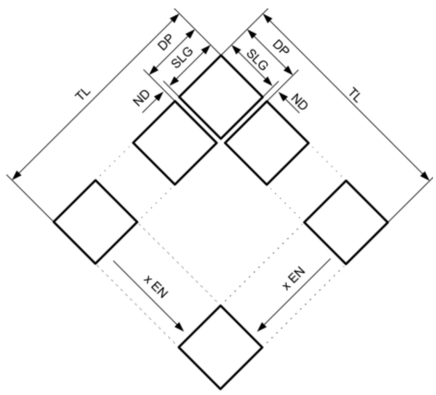

Fig. 3 Diagrams for deriving equations for the size and number of Grid infill elements

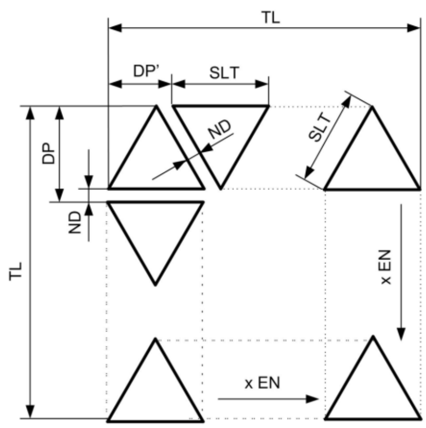

Fig. 4 Diagrams for deriving equations for the size and number of Triangular infill elements

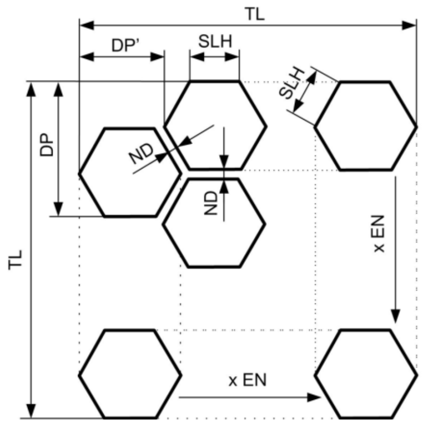

Fig. 5 Diagrams for deriving equations for the size and number of Honeycomb infill elements

The length of the side of a square, triangle or hexagon must be determined on the basis of the infill density and the diameter of the nozzle. The empty space between the 3D printed pattern complements the infill density. The infill must cover the entire object, hence the output value for calculations is the surface area of a square with a (TL) side not smaller than the largest dimension of the base of the 3D printed object, for a given orientation on the printer table. The number of layers, i.e. the infill height, must be not less than the third dimension (height) of the 3D printed object. The number of elements (EN) in the rectangular pattern, the distance between elements (ND) together with the element size and nozzle diameter are closely related (formula 1). Pattern spacing is the distance between elements in both directions (DP). For Grid infill, DP is pattern spacing for both directions. For Triangular and Honeycomb, DP is pattern spacing for one direction and DP for perpendicular direction.

Taking into account the presented assumptions, relevant relationships were derived. After their transformation and simplification, quadratic equations were obtained for each infill:

$$\begin{cases} -ID \cdot SLG^2 + (2ND - 2ND \cdot ID) \cdot SLG + ND^2 \cdot (1 - ID) = 0 \\ -\sqrt{3} \cdot SLT^2 + (6ND - 6ND \cdot ID) \cdot SLT + 3\sqrt{3} \cdot ND^2 - 3\sqrt{3} \cdot ND^2 \cdot ID = 0 \\ -3\sqrt{3} \cdot ID \cdot SLH^2 + 6 \cdot ND \cdot (1 - ID) \cdot SLH + \sqrt{3} \cdot ND^2 \cdot (1 - ID) = 0 \end{cases} \quad (1)$$

where:

ID – infill density expressed as a decimal fraction, [-],

ND – nozzle diameter which is the thickness of the infill wall, [mm],

SLG – length of the Grid element side, [mm],

SLT – length of the Triangular element side, [mm],

SLH – length of the Honeycomb element side, [mm].

The above dependencies have been saved in the form of an iLogic script that enables generating infills. The script has been equipped with a form for entering the size of the element, height, type of infill, outside wall thickness, nozzle diameter and infill density. The final object is a union of the object shell and the intersection of the infill and the object (Fig. 2). The same effect can be achieved in any CAD programme that enables creating scripts or cooperates with an external spreadsheet.

VALIDATION OF THE METHOD AND THE TOOL

The infill generator was validated in order to check both the method and the tool. The effects obtained with corresponding infills generated by various programs dedicated to 3D printing were compared. In addition to the Simplify program, UltiMaker Cura and PrusaSlicer were also used. The infill density was also verified by calculating its value on the basis of the surface area of the pattern in relation to the total surface area.

Fig. 6 shows an example of generated Grid infills with a infill density of 50%. The infill patterns obtained from the generator (Fig. 6a) and the UltiMaker Cura programme (Fig. 6b) are identical, which can also be seen in their assembly (Fig. 6c).

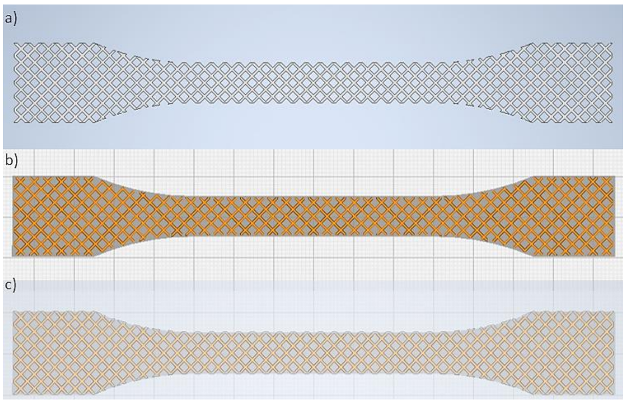

Fig. 6 50% Grid infill:
a) infill generator, b) UltiMaker Cura dedicated programme, c) assembly of infills

Similarly, an example of a comparison for the HoneyComb infill shown in Fig. 7 for ~~a~~ an infill density of 25% was made in the PrusaSlicer programme. Fig. 7a shows an infill from the generator, Fig. 7b from PrusaSlicer, and Fig. 7c their assembly. The obtained patterns are consistent. Fig. 6 and Fig. 7 show a sample comparison ~~effects~~ of the effects for the HoneyComb and Grid infill, but the same process of validation was performed for the Triangular infill.

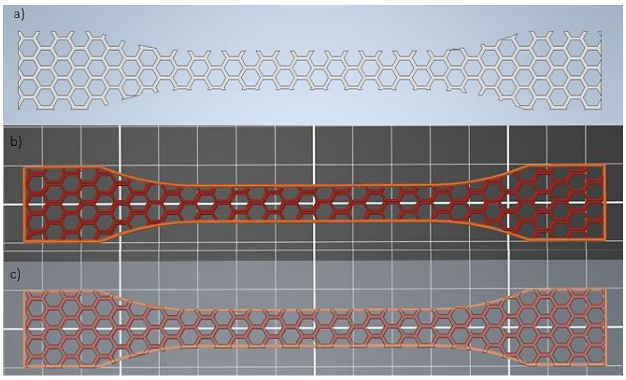

Fig. 7 25% HoneyComb infill
a) infill generator, b) PrusaSlicer dedicated programme, c) assembly of infills

As a result of the generator's operation, we obtain a 3D model of an element, which initially consists of two independent solids, i.e. the external outline and the infill. Therefore, in order to check whether the element behaves as one solid, verification was carried out with the use of simple FEM tests. The previously presented shape of the standardized sample was chosen as the object. The samples are intended for uniaxial tensile strength testing and such a case was simulated. All types of infills were checked for various infill density, while analysing displacements and reduced stresses (Fig. 8). The obtained results confirmed the correct operation of the generator.

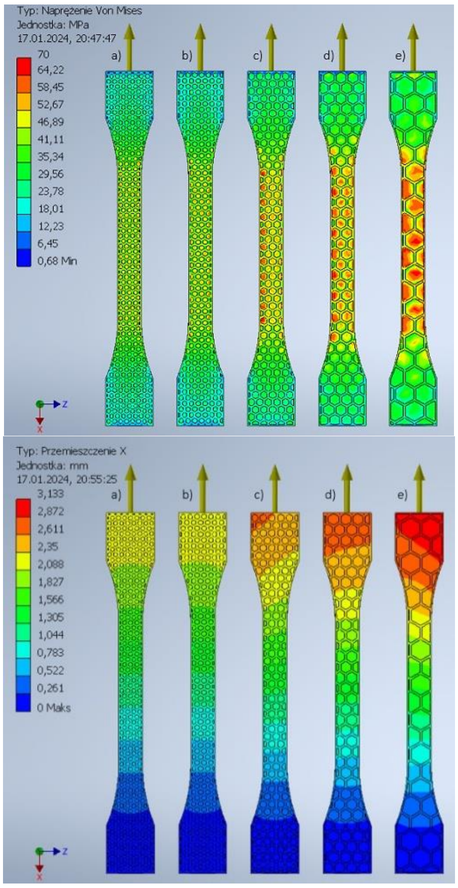

Fig. 8 Reduced stresses and displacements for the HoneyComb infill: a) 50%, b) 45%, c) 35%, d) 25%, e) 15%

USE OF THE GENERATOR FOR ANALYSES REGARDING REAL OBJECTS TO BE 3D PRINTED – EXAMPLES

The developed generator enables performing valuable analyses before an element is 3D printed. The cost of a piece related to the 3D printing duration and the amount of material can be minimized. Preliminary analyses make it possible to determine the optimal parameters and 3D printing orientation. Below have been presented three examples of the generator's use for assessing the strength and stiffness of real pieces:

- influence of the orientation while 3D printing of a 3D printed pin,
- influence of the infill pattern on a 3D printed hook,
- influence of the infill density on a 3D printed connector.

In the first example, simulations for a 3D printed pin with the following parameters: the Honeycomb infill, a nozzle with a diameter of 0.4 mm and a infill density of 40% (Fig. 9) were carried out for three different, perpendicular 3D printing orientations (Fig. 10).

Fig. 9 Pin used for analysing the influence of 3D printing orientation

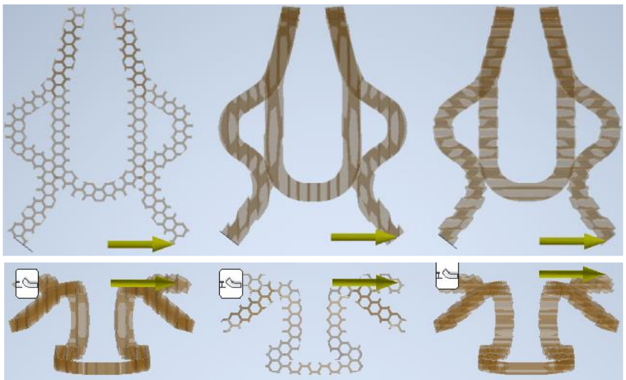

Fig. 10 Pin infills for three perpendicular 3D printing orientations

The pins were fixed on the face of one end and loaded with an outward force on the face of the other end. As a result, the pins were deformed in a very similar way, achieving a maximum displacement of approximately 6.7 mm. However, the reduced stress differed significantly. The maximum stresses reached 16.16 MPa, 9.34 MPa and 13.05 MPa (Fig. 11). This means that a change of the 3D printing orientation alone results in a difference in maximum stresses of up to 73%. In the case of a similar analysis, but with the force directed upwards, the difference exceeded 120%.

It is important to bear in mind that supports need to be provided when 3D printing such a pin. This affects the 3D printing time, which will vary depending on the orientation, as shown in Fig. 12.

In the sequence of orientations shown in Fig. 9, the filament mass and 3D printing time are 4 g/21 minutes, 3g/21 minutes, 5g/27 minutes. Differences in the 3D printing time and filament weight are significant. The second orientation is the most favourable in terms of durability, 3D printing time and filament consumption (Fig. 13).

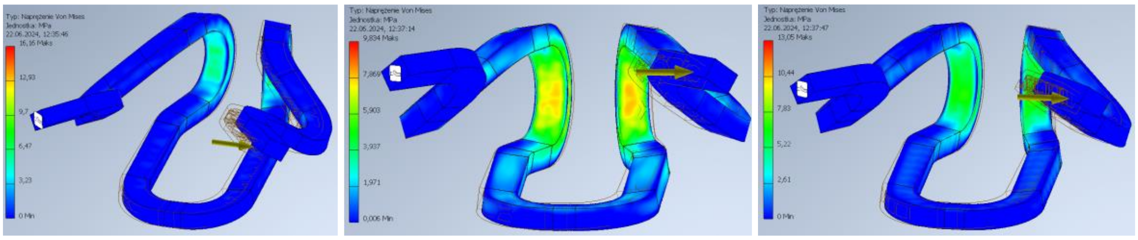

Fig. 11 Reduced stresses in pins for different 3D print orientations (sequence as in Fig. 9)

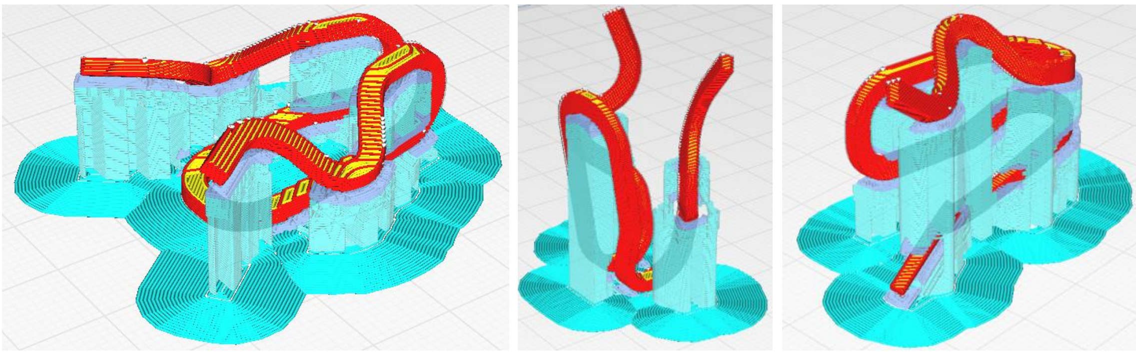

Fig. 12 Pin in three different orientations prepared for 3D printing with supports (turquoise)

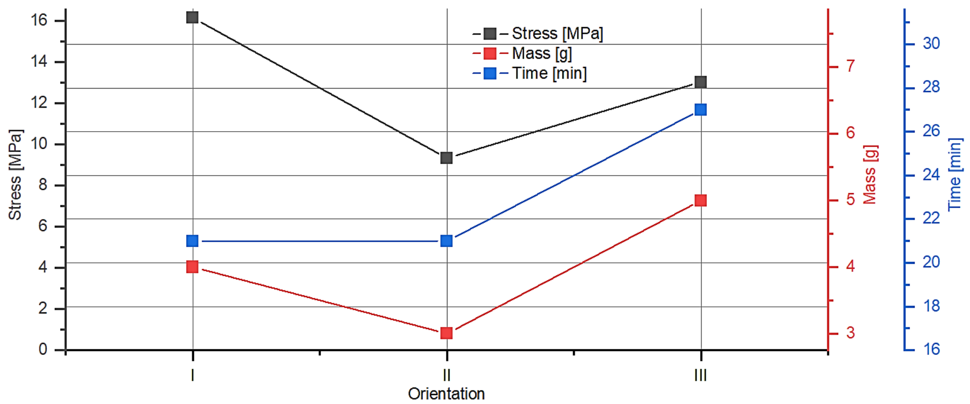

Fig. 13 List of 3D printing parameters and cotter pin strength

The subsequent analysis was aimed at selecting the type of infill for 3D printing a hook. The infill density was assumed to be 35% for the Grid, Triangular and Honeycomb infills (Fig. 14). The hook was fixed and loaded with a force. The conducted FEM analysis revealed that for the Grid infill the stresses reached 34.8 MPa and the displacement – 2.2 mm; for Triangular – 27.9 MPa and 1.9 mm, and for Honeycomb – 29.0 MPa and 2.0 mm. Selected projections are shown in Fig. 15.

The third simulation test was aimed at illustrating the influence of the density of a piece infilling on the maximum stress, displacement, mass and time of 3D printing of the element (Fig. 16).

The connector of the gripper mechanism loaded with a force was selected as the object. Models with 10% to 80% infill density were analysed. The results are presented in the form of a graph in Fig. 17. Such an element with 100% infill density has a mass of 64 g, moves a maximum of 0.49 mm, and the stresses reach 3.6 MPa.

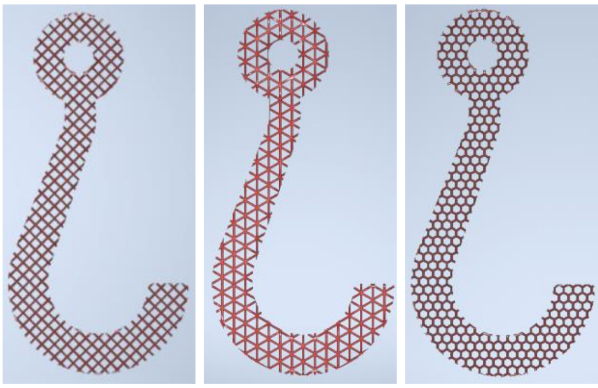

Fig. 14 Density 35 % – grid, triangular and honeycomb infill of the hook

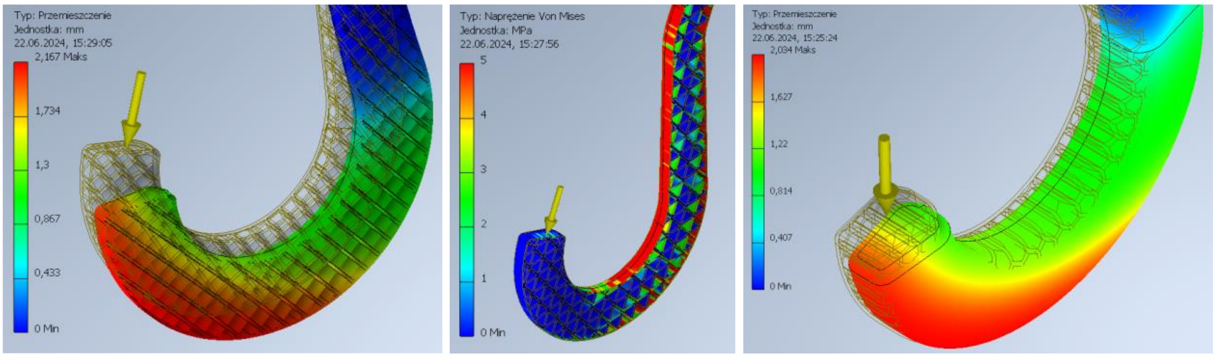

Fig. 15 Results of FEM calculations for 35% grid, triangular and honeycomb infills of the hook

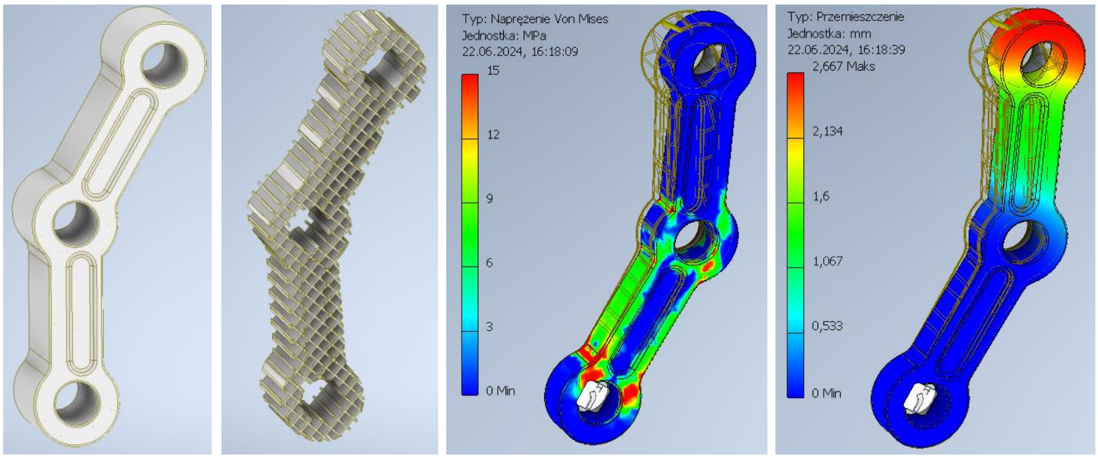

Fig. 16 Connector: model, infill, selected analyses

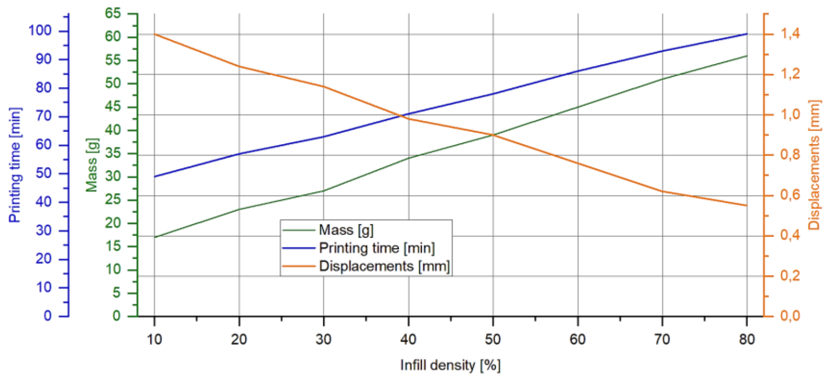

Fig. 17 Chart of the maximum displacement, mass and the time of 3D printing of the connector

The 3D printing time and mass of an element increase with the infill density, which also increases stiffness. Assuming the permissible stress or displacement of the connector under load, one can select the infill density as well as estimate the 3D printing time and its mass. It is also worth taking into account some additional indicators referred to as W1 and W2, which are the quotient of mass by maximum stresses and by maximum displacements, respectively (Fig. 18).

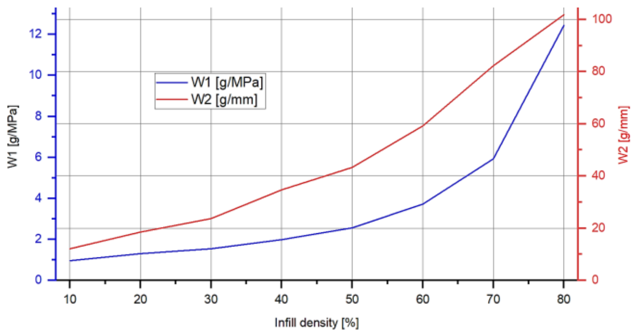

Fig. 18 Graph of the W1 and W2 mass indicators for the connector print

These indicators show how many grams of filament are required to achieve a stress of 1 MPa and a displacement of 1 mm. As the indicators increase, the profitability of the 3D print decreases in terms of its strength and stiffness. It is worth noting that while in the previous chart the values changed almost linearly as a function of the infill density, the W1 and W2 indicators change exponentially.

CONCLUSIONS

The aim of the works described in the article was to create a method and tool for converting typical 3D models into models with infills compatible with those used in 3D printing. The developed method and the iLogic tool of Autodesk Inventor were used to create a generator of 3D models with a infill. From among numerous available type of infills, the most popular and frequently used were selected, i.e. Grid, Triangular and Honeycomb. The derived mathematical relationships were based on basic assumptions. The infill density is the ratio of the 3D printed surface area to the total surface area. The thickness of the element's wall is equal to the diameter of the nozzle. Taking into account the infill density and the diameter of the nozzle, depending on the type of infill, the length of the side of an element(square, triangle or hexagon) is calculated. Next, arectangular pattern of required size and number of elements elements is generated. Using the operations of the intersection and the union (Boolean operations), the infill and the 3D model of the object ultimately create the target object with a infill.

The infills obtained as a result of the generator's operation were compared to those from dedicated programs (Simplify, UltiMaker Cura and PrusaSlicer), which allowed confirming the correct work of the generator. The calculated ratio of the infill area to the total area also corresponded to the set infill density. The next stage of tool validation involved FEM testing of the samples and evaluating the obtained results, which also confirmed that the generator was working properly.

The generator can be used to select 3D printing parameters for objects of any shape and loading method. The article presents three examples of the generator's use for analysing real objects. There have been described generator applications for assessing the strength and stiffness of pieces, aimed at selecting the orientation of the pin during 3D printing, the type of hook infill and the infill density of the connector. Each of these elements was subjected to a specific load. The obtained results have confirmed that preliminary numerical tests of the object enable increasing its strength and stiffness or reducing its weight and 3D printing time, depending on the needs. The generator delivers 3D model for FEM tests.

The developed method and generator have a great potential and provide first aid when selecting the orientation, type and infill density of a 3D print for elements that carry specific loads.

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