3-D Modelling and prototyping of complex-shaped heterogeneous parts

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Abstract. This article provides a description and results of a study of the feasibility and applicability of encapsulation of various elements in parts of complex shapes, produced using 3-D printing and 3-D modelling. The relevance of this study is confirmed both by the general high rate of development of 3-D printing technologies in the world, and by the abundance of innovations in the application of these technologies, as well as by the specific features and needs of the specific production of optical sensor prototypes. This article describes the stages of the process and provides examples of encapsulated elements. A set of programs was used to create and modify gCode files in order to carry out the experimental part of the study. Experiments on the encapsulation of fasteners, insulating elements and elements of optical paths were successfully carried out in the course of the study in order to estimate feasibility of these encapsulation techniques. The objectives of the study have been achieved. The results or the research allows us to outline further ways of research, as well as to note the possibility of developing a single software package combining the functions of a slicer and gCode editor.

1. Introduction

In the course of optimizing the development of optical sensors for liquid pollution based on the principles of speckle interferometry [1], 3-D printing and 3-D modelling technologies were successfully applied [2]. These techniques were used in different interpretations for manufacturing various parts of optical sensors. Based on the gained experience, analysing available technologies and taking into consideration more complex requests arising about prototyped parts, it was decided to continue further studies of the applicability of these technologies for encapsulation of different objects inside of the 3-D printed part during the printing process.

In this article, encapsulation means emplacement of an element into a printed part by creating a corresponding cavity in its model for placing this element in it and further modifying the gCode file in order to set a technological pause in the printing process for placing the encapsulated element. After this action and the operator's confirmation command printing continues, imprinting the encapsulated element into the part.

The object of this study was various heterogeneous parts and other objects manufactured using fused deposition material 3-D printing technology and encapsulation of various objects and materials.

The subject of the study was the feasibility and applicability of heterogeneous objects, their intercompatibility, adhesive, thermal, strength, shielding and other qualities, the prospects of their manufacturing in general.
The relevance of this study is confirmed both by the general high rate and volume of development of 3-D printing technologies in the world [3], and by the abundance of innovations in the application of these technologies. As a promising example of the implementation of additive technologies in high-tech research processes, it is worth mentioning the research of the Department 316 of the Moscow Aviation Institute, aimed at increasing the efficiency of applying changes to models and prototypes of space rocket nose cones [4]. The study of encapsulation of various elements into various details is currently not widely covered yet, which allows us to speak about the scientific novelty of our study.

2. Methods and materials

2.1 Production methods and materials used

Fused deposition modeling (FDM) technology was used in this study to fabricate the experimental parts. FDM is a technology of parts creation by means of layer-by-layer deposition of thin filaments of plastic passed through an extruder. The flexibility of printing patterns customizing makes it possible to create various configurations of parts, both solid with 100% filling and lightweight parts with different types of honeycomb filler inside, which can have different densities. The type of filling can be set when preparing files for 3-D printing. Different types of filaments can be used for FDM 3-D printing due to wide range of temperature conditions at which the extruder can operate.

Polylactide plastic (PLA) was used for this study. Its properties are convenient for experiments: this plastic is fairly strong, it does not require an additional closed thermal chamber of a 3-D printer and it has an extremely low (<1%) coefficient of thermal shrinkage when the part cools down.

2.2 Encapsulation methods considered

Different techniques for encapsulating elements with various properties and parameters, as well as the purposes of final usage were considered in this study. The main groups into which these elements can be divided are the following:

- Fastener Encapsulation: Increases the strength of threaded connections by reinforcing them with melted into the material and imprinted fasteners. Screw nut was used as a testing fastener in our experiments. 3-D model of a testing cube contained an octagonal cavity suitable for the screw nut including fit tolerances. This batch of experiments allowed us to study differences between built-in encapsulated fasteners and screw thread, which was cut in a raw plastic detail or gained via 3-D printing. The results of the tests show that encapsulated fastener is more versatile and holds details much better than the printed or carved screw thread.

- Reinforcing elements encapsulation: increasing the strength of parts of various frames for bending and twisting due to their reinforcement with various wires, meshes and other reinforcing elements.

- Encapsulation of glass and similar materials: creation of optical paths, light guides, glass fibres and other solutions that are commonly used in prototyping various optical sensors.

- Encapsulation of shielding elements: the use of amorphous metal tape, fine-mesh metal nets and other similar materials to shield the contents of the enclosures from electromagnetic radiation.

- Encapsulation of other objects: including other necessary elements in the details depending on the requirements of the situation, which are applicable, for example, to create various electronics and other parts [5].

As an example, the conceptual model of the reinforcement of a part using a metal mesh is shown on the figure 1. The detail is shown in partial section; the mesh reinforcing part is imprinted into the plastic.

2.3 Encapsulation features to be considered

Encapsulation implies the interaction of various materials in a fairly wide range of temperature effects (delta of temperatures is about 150 degrees centigrade). Therefore, it is necessary to take into account
many parameters of these materials when preparing models for creating a heterogeneous body with an element encapsulated directly in the process of 3-D printing. The most important groups of parameters that actively influence the results of encapsulation are discussed below.

![Figure 1. Example model of encapsulated reinforcement mesh.](image)

2.3.1 Thermal expansion and shrinkage coefficients of combined materials. These parameters are taken into account to ensure a precise fit of the encapsulated element into the cavity prepared for it in the part. When the printing process is stopped, cooling of the printed part starts due to the lack of passive heating from the movements of the hot nozzle above it. This cooling causes shrinkage of the material. The thermal shrinkage coefficient of filament specified by its manufacturer is taken into account during the modelling stage for correction of the fit tolerance. The thermal shrinkage factors of encapsulated elements are specified in specialised literature or manufacturers’ datasheets, dedicated to every specific filament type. These datasheets usually contain information about exact shrinkage coefficient (which differs a bit between manufacturers because of different coloring additives and some other specific technological features), recommended printing temperature and other parameters of plastic.

2.3.2 Adhesion of materials to be combined. Since the adhesion of plastic to smooth surfaces of glass or metal is not sufficient to form a reliable "sealing" layer, it was decided to use a glue-like binder that allows the layers to be confidently formed even on the surface of smooth encapsulated elements. Such a substance is an alcohol-acrylate solution applied to surfaces in the form of a micro-dispersed spray, whose excess, if necessary, is removed after printing by means of chemical cleaning.

2.3.3 Thermal stability of the encapsulated material. Some materials degrade or break when exposed to the high temperature of the extruder nozzle and hot plastic. For example, some classes of neodymium magnets lose their properties. Subsequently, it is necessary to take into account the properties of the encapsulated materials and try to avoid situations that can cause degradation of their properties. Additionally, strength and temperature interactions can be analysed using specialised software for simulating such interactions [6].

2.3.4 The strength of the “sealing” of the encapsulated object. In the case of encapsulation of various functional objects it is necessary to eliminate the strength difference between the sintering of print layers over a cooled layer and over a layer recently printed and not yet fully passed the glass transition threshold. Slight increase of the temperature and plastic flow while printing continues can ensure maximum interlayer adhesion of the plastic layers [7].
2.4 The main stages of manufacturing heterogeneous objects using encapsulation

2.4.1 Part design and modelling. The process of producing a part with an encapsulated element starts at the stage of creating a 3-D model of the part. The position of future inclusions of other objects into the part is set at this stage, taking into account the required fit tolerance, the coefficients of thermal expansion during heating and the subsequent shrinkage of plastic and encapsulated element. Despite the fact that the effect of thermal shrinkage of materials in 3-D printing is weakened due to the partial cooling of the melt when passing through the nozzle and hitting the filament on the printed part, there is still some degree of shrinkage, which varies depending on the specific type of plastic from 0.1% to 4%. Specific values for the most commonly used materials in 3-D printing are given in the data sheets by the manufacturers of specific plastic, but on average, PLA plastic gives no more than 0.1% shrinkage, when ABS plastic gives up to 1–1.5%. Subsequently, a bed for the encapsulated element should be wider to avoid cracking of this element and/or printed plastic under cooling. As an example, one of the first testing subject models is shown on figure 2 below.

A cavity for the encapsulation of the glass plate is created at the stage of the modelling taking into account the fit tolerance and the thermal shrinkage coefficient of the PLA plastic used for the experiment with the declared shrinkage of 0.8%.

2.4.2 Translation of the solid model into the gCode instruction set. On this stage the solid model is loaded into the slicer program, where the position of the part on the working surface of the 3-D printer is set. The temperature and speed characteristics of printing, the percentage of the internal filling of the part and other characteristics [8] are also set and interlayer mark tags are placed. Tagging is used to structure the gCode file which transforms it from a solid array of 3-D printer commands into a well-structured layered file. The beginning and end of the layer, the beginning and the end of the whole printing process, as well as some other states and actions are tagged. The same testing unit is represented the figure 3 by slicer UI already sliced and prepared to be edited.
As can be seen in this figure, low printing speed were used for the first experimental prints to ensure sturdy plastic-glass adhesion.

2.4.3 *gCode file modification*. The gCode file obtained at the previous stage is opened in the third-party gCode editor program, which reads layer tags and allows more convenient viewing in graphical form and editing layers by inserting sequences of commands. Technical pauses are set for placing the encapsulated elements on the part on the specific tagged layers, a set of instructions is set to wait for the continuation of printing at the operator's command. This is shown on figure 4. For this stage, a modified, renewed and refined version of the open-source “gCodeEditor” program is used. Modification of the freely published [9] source code was necessary for compatibility with the Simplify3-D slicer and custom layer tags used in the experiments as well as some other refinement of command pasting functions and templates.

![Figure 3. Slicer UI representation of sliced testing unit example.](image)

![Figure 4. Modified gCode Editor UI with testing unit and insertable pause sequence representation.](image)
Figure 5. Formal representation of the encapsulation process.
2.5 Formal representation of the encapsulation process
Since the process of encapsulation of any of the considered elements has clearly defined stages and similar features, it is possible to form a general algorithm of actions and present it in a formalized form of a process diagram presented on the figure 5. The figure 5 is divided into four main blocks to illustrate the four main sections of the encapsulation process. Three of them are carried out using various software, while the latter is performed directly on a 3-D printer.

3. Results and discussion
Theoretical study of the feasibility of encapsulation showed that the encapsulation of many elements can be implemented even with fairly simple hardware. In addition, sets of encapsulation features for many materials have been analyzed and formed. A series of experiments were carried out, the results of which were included in this article.

3.1 Part printing and encapsulation
This stage includes primary printing, encapsulation and final “sealing” printing. At this stage of the study the installation of the encapsulated element was carried out manually with observing certain conditions:

- Cleaning of the encapsulated element from possible dust particles and pollutions.
- Degreasing the encapsulated element with a solvent or alcohol compatible with the material used.
- Application of an additional adhesion promoter, if required. An alcohol-acrylate solution in the form of a spray was used as such a substance.

Upon further sealing of the encapsulated element from the high temperature of the nozzle the acrylate base fused and partially evaporated from the plastic surface, providing a high degree of adhesion of the first plastic layer with the material of the encapsulated part. Figures 6-8 demonstrate the results.

![Image](image.jpg)

**Figure 6.** Glass part encapsulation. Glass glare may be seen in the centre section of the frame.
Figure 7. Testing of amorphous metal tape encapsulation. Demonstration port for visibility.

Figure 8. Testing of fastener encapsulation. Example cube with screw nut inside.
3.2 Dimensional characteristics, tolerances and their effects

Analyzing the processes of parts production we took into account the factors influencing the geometry of the parts (manufacturing error, material expansion, etc.). These factors can be divided into the following conditional groups:

- Manufacturing tolerances. These tolerances were taken into account when designing parts and in software preparation due to the presence of an established error in the accuracy of the 3-D printer. For the 3-D printer model Anet A6 used in the experiments, the manufacturer declared 12 micrometers as an admissible error in the positioning of the extrusion unit along the X and Y axes (horizontal movement). The positioning error along the Z axis is about 4 micrometers. But this possible inaccuracy of positioning is much less than the diameter of the nozzle used in the experiments (0.4 mm), so the real definition of the printing process is about 0.4 mm along X and Y axes. The positioning error along the Z axis is about 4 micrometers but the real minimal thickness of the layer is about 0.1 mm.

- Material expansion tolerances. As mentioned above, the declared shrinkage of PLA filament does not exceed 1% upon cooling. The real measured average shrinkage of plastic used in the experiments was about 0.78%. This value was obtained by sequentially printing and measuring a series of test parts with holes of a pre-specified size immediately after calibrating the kinematics of a 3-D printer in order to separate the known positioning error from the effect of thermal shrinkage.

- Tolerances of fit of a particular encapsulated element. The values of tolerances differ, since the encapsulated elements also have a significant differences in manufacturing parameters. Thus, it was experimentally found that encapsulated glass plates have the biggest errors. Deviations in thickness, dimensions in the plane and even deviations of cut angles from 90 degrees were noted within the purchased batch. As a result an individual adjustment of tolerances in the 3-D model was required. The other solution of this problem is an additional processing of glass plates, as well as the purchase of a more accurately manufactured batch. The opposite case was the encapsulation of the electromagnetic shielding material (amorphous metal tape). Since the thickness of the tape (less than 20 mkm) is less than the thickness of the minimum supported printing layer for this 3-D printer (0.1 mm), then the landing tolerance was not applied during its encapsulation. The admissibility of this solution was confirmed experimentally. A slight shift in the height of the plastic laying was compensated by the density of fusion of the subsequent layers both horizontally and vertically. When the fasteners were encapsulated, the fit tolerance corresponded to the values given in the instrumentation manuals for the corresponding cavity sizes, so in this case there are no interesting features.

Based on these experiments, an ordered methodology for the encapsulation process is formed, presented in the form of a functional diagram. At the moment, the topic of encapsulation in 3-D printing is partially covered, but it is most actively used at the level of microscopic additive technologies [10] and preparations, adaptation for FDM, SLS and other technologies is not widely covered.

4. Conclusion

The primary goals of the study have been met. A number of issues related to the combination of various materials and objects in one heterogeneous part were solved, and a primary method of manufacturing such parts was formed as a result of the study. Promising directions for the refinement and improvement of this technique were outlined, and further software and hardware solutions were noted that would expand the capabilities of this technique:

- Combining several types of plastics directly during the printing process to reinforce and strengthen the structure.
- Study of tightness and pressure resistance.
- Further development of chemical and thermal post-processing of products.
- Encapsulation of objects of a more complex shape, requiring more degrees of freedom of movement of the extrusion module.
- Development and creation of a software package that combines the functions of a slicer and an advanced editor gCode.

Considering all of the above, we can say that this study has brought positive results and gave rise to a wide range of further research promising and interesting from a technological point of view.

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