ISSN 2303-4521
*Original Research*
**Periodicals of Engineering and Natural Sciences**
Vol. 9, No. 4, September 2021, pp.443-441

# 3D printed solder masks for printed circuit boards

**Andrei Gorelov[1] *, Fedor Vasilyev[1]**
[1] Department of Digital Technologies and Information Systems, Moscow Aviation Institute (National Research University)

**ABSTRACT**

The use of additive technologies in the creation of soldering masks opens up new opportunities in the production of printed circuit boards, in particular, the use of soldering masks for boards with integrated components. The paper considers the results of experimental data on the adhesion of 3D soldering masks (that is, masks created on a 3D printer) obtained during the study of the introduction of 3D printing into electronic manufacturing processes. For the analysis of adhesion, it is possible to use such methods as breaking load, cross-cut test, and the sticky tape method. A number of experiments were conducted to study the adhesion by testing the breaking load. The samples were formed with different ratios of prepreg/solder mask, then the force at which the fracture occurred was measured. The essence of the cross-cut test is to apply at least three parallel cuts and perpendicular to them also at least three parallel cuts with the tip of the cutter. After the scratching, there must be no flaking of the coating between the lines and in the grid of squares, then the results are assessed. Sticky tape tests are performed by applying the tape with the adhesive side to the test sample with a cured coating applied. The results are assessed by visual inspection using an optical device that provides 3x magnification. The results of the breaking load experiments indicate that 3D masks show comparable separation forces with a prepreg. At the same time, the force is stable for all types of surfaces and practically does not depend on the thickness and configuration of the 3D mask. Experiments with applying cross-cuts show consistently good results with a homogeneous base material – there are no coating detachments. The paper concludes that the use of 3D soldering masks on the inner layers of multilayer printed circuit boards with built-in components is possible, but a number of issues must be solved for this, including those related to the software for forming 3D structures of masks.

**Keywords**: Adhesion, Embedded components, Reliability, Soldering, Additive technologies.

***Corresponding Author:***

Andrei Gorelov
Department of Digital Technologies and Information Systems
Moscow Aviation Institute (National Research University)
125993, 4 Volokolamskoe Shosse, Moscow, Russian Federation
E-mail: 2652045@gmail.com

## 1. Introduction

Practically no printed circuit board is produced today without a soldering mask. Solder masks protect the conductors from short circuit, corrosion and, most importantly, from solder outflow during soldering. There is a wide variety of soldering masks. They differ in composition (one-component/two-component), type of curing (thermal/photo-curing), condition (liquid/dry film), colour, surface type (glossy/matte), etc. Each type of soldering mask can have both advantages and disadvantages. For example, liquid solder masks fill small gaps between conductors better than film masks, but at the same time they have worse covering power – the sharp edges of the conductors can be exposed, which can lead to problems during use, in particular to electrochemical migration [1; 2].

Photoformable soldering masks can be liquid and dry (film). The polymer material of the mask has a different thickness. For a liquid mask, the final thickness is usually from 0.02 to 0.025 mm. For dry masks, the film photoresist usually has a thickness of 0.04 mm, 0.08 mm and 0.1 mm. When using a liquid solder mask, the accuracy of aligning the cutouts in the mask with the topological pattern of the board is significantly higher than when using a dry film photoresist [3]. The process of applying soldering masks of all types is similar: a soldering mask is used (depending on the type of mask, this can be, for example, lamination of a dry film photoresist or spraying of a liquid photoresist), then exposure through a photomask or by direct exposure, then development and drying (also depends on the type of mask). At the same time, conventional soldering masks have significant limitations: they have the same thickness over the entire area of the board, and they cannot be used for the inner layers of multilayer printed circuit boards with embedded components.

In turn, additive technologies open up broad prospects in various spheres: mechanical engineering, architecture, medicine, construction, and everyday life. However, 3D printing technologies are not so widespread in the field of electronics production and are mainly used in the field of manufacturing prototypes of housings, fasteners, and other auxiliary elements [4-8]. Currently, a lot of research is being conducted on the introduction of additive technologies in the production of printed circuit boards (PCB), 3D printers are being developed for the manufacture of printed circuit boards, including PCB with components. However, these developments are still far from industrial applications. The purpose of the research at the department "Digital technologies and information systems" of the Moscow Aviation Institute is expanding the field of using additive technologies for the production of printed circuit boards, namely, for obtaining soldering masks by 3D printing (“3D masks”) [9; 10]. At the same time, 3D masks have additional functions: they can be used to fix components located on the outer layers of printed circuit boards, and on the inner layers of multilayer printed circuit boards with built-in components, where the use of traditional soldering masks is virtually impossible, which leads to the need for passivation of the conductive pattern, to complicate and increase the cost of the technological process as a whole [11; 12]. The purpose of this study is to investigate the fundamental possibility of using 3D soldering masks in electronics by assessing the adhesion of masks to printed circuit boards, both on the external and internal layers of PCB.

Increased requirements are imposed on printed components of aviation equipment in terms of reliability, including vibration resistance [13]. To increase reliability, components are often fixed to the board with adhesive. Experience shows that under the influence of loads, it is possible to detach the component together with the solder mask from the board in the area of adhesive fixation, which leads to the failure of the nodes. This, in turn, indicates insufficient adhesion of the solder mask to the printed circuit board in the case of using adhesive fixation of components [14]. The use of solder masks with good adhesion and/or made of a material similar to the material of printed circuit boards (fiberglass laminate, for example) could improve the situation. This possibility is offered by 3D printing using stereolithography and PolyJet methods. 3D printing also allows applying a relief that will additionally hold components on printed circuit boards. To do this, we need to create 3D model for the mask in a format appropriate for a 3D printer [15]. The material has a glass transition temperature from 50 to 120°C, which allows “gluing” electronic components to the printed circuit board with the mask itself during the convection soldering process. It is desirable that the mask is not completely cured during printing. In this case, during soldering, additional curing of the mask will occur, which will further increase the strength of the joint.

## 2. Material and methods

As a result of convection soldering, a more rigid structure of the node is obtained, which allows better withstanding mechanical influences. In addition, applying a coating of the same material on top of electronic components after their installation on a printed circuit board can provide moisture-proof properties of the printing unit by creating a monolithic structure [16]. A 3D mask on the inner layers of multilayer printed circuit boards with embedded components [17] can also perform the functions of a prepreg. That is, when pressing, the mask will “flow”, filling the voids and gluing the layers together. At the same time, the thickness of the masks and the volume of the material may vary for different sections of printed circuit boards. When using a prepreg in the manufacture of printed circuit boards, the pressure “takes out” the prepreg and the movement of a large amount of resin contained in the prepreg affects the components, which, in turn, often leads to shifts of the components and the occurrence of internal stresses. However, in the case of using 3D soldering masks, these stresses can be minimized due to the different dosages of the material in different parts of the printed circuit board.

Another important point: the temperature usually used when pressing multilayer printed circuit boards is about 180°C, which actually excludes the use of traditional PbSn-type solders for fixing components on the inner layers. Despite the RoHS directive, the use of lead-free solders is limited in high-duty equipment. The use of 3D masks allows reducing the pressing temperature to 150°C and below, and the use of PbSn solders becomes possible [18]. The question of the reliability of printed circuit boards using 3D soldering masks remains open. How such boards will behave during pressing, drilling, and metallization [19; 20]. Partially, these issues can be solved by conducting modeling [21], but it is possible to unequivocally answer the question of the suitability of 3D printing for obtaining solder masks only with a large number of versatile studies.

For a full-fledged study, it is necessary to consider a number of parameters of materials proposed for use as a soldering mask:

- adhesive strength – the protective coating must be firmly held on the surface of the protected material;
- dielectric properties – the protective coating should provide insulation of printed conductors;
- resistance to environmental factors – the protective coating must retain its properties under the influence of high humidity, high and low temperatures, and their changes, etc.
- For the study of adhesion, it is possible to use the following methods:
- breaking load – applicable for testing the adhesion between the layers of a multilayer printed circuit board, since this solder mask is being considered for use in printed circuit assemblies with embedded components;
- cross-cut test (ISO 2409:2020) – checking the adhesion on the outer layers of the printed circuit board; despite the fact that the standard does not directly apply to soldering masks, many coatings are often tested by this method. In addition, the material of 3D soldering masks is radically different from the classical materials used as conventional soldering masks, which requires additional experiments;
- adhesive tape method (IPC SM 840) – "classic" method for testing the adhesion of a solder mask [22].

## 3. Results and discussion

*Experiment 1. Breaking load.* A number of experiments were conducted to study the adhesion by testing the breaking load. The samples were formed with different ratios of prepreg/solder mask, then the force at which the fracture occurred was measured. The material of the samples – ISOLA fiberglass laminate FR-4 (brand DE-104). The 3D printer is a modified Objet Connex 260. The material of the soldering masks – FullCure720, Tg=50°C.

The structure of the investigated board (Figure 1):

1. The base is 120×80 mm in size and 1.5 mm thick with the described zones.
2. Binder (prepreg, 3D mask, or a combination of them).
3. The upper part is 1.5 mm thick, similar to the base.

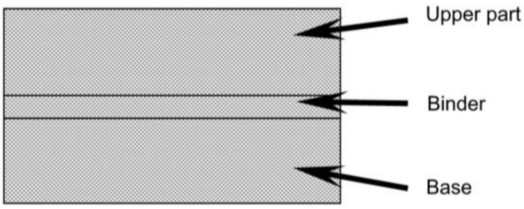



Figure 1. Circuit board structure

To simulate conductors on printed circuit boards, three zones are located on the test samples (Figure 2):

– pure fiberglass laminate;
– solid foil;
– a diagonal grid of conductors with a width of 1 mm with a distance of 4 mm.

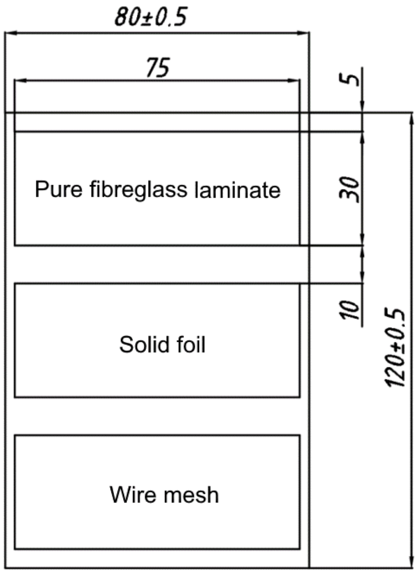



Figure 2. Zone layout

The appearance of the base is shown in Figure 3.

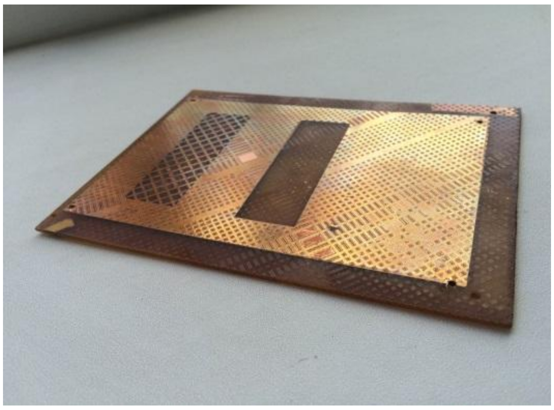


Figure 3. The appearance of the base

After pressing, the upper part is divided by milling into elements with a size of 5×5 mm, so as not to damage the base (Figure 4), to which the hooks are then attached (Figure 5). This design of the samples ensures a stable gap in the area of the binder.

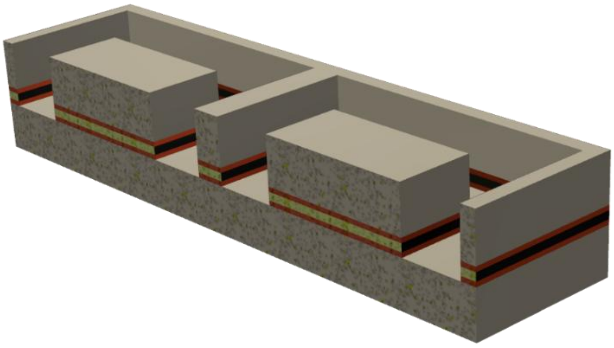


Figure 4. Cross-section of the sample model for testing the breaking load

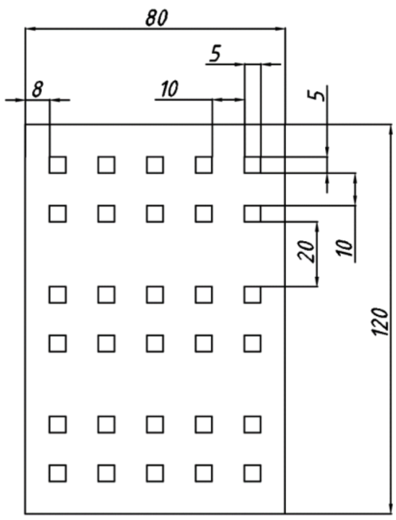



Figure 5. Element contours

The adhesion of the mask is assessed by measuring the separation force of the elements. The following groups of samples (with binders) were manufactured:

– 3D mask of 60 µm solid;
– 3D mask of 90 µm solid;

– 3D mask of 60 µm mesh;
– 3D mask of 90 µm mesh;
– prepreg;
– prepreg plus 3D mask of 60 µm solid.

This results in 18 different surface/binder combinations. Two samples are made for each of the variants, which gives a total of 20 measurements for each option of the surface/binder combination (Figure 6).

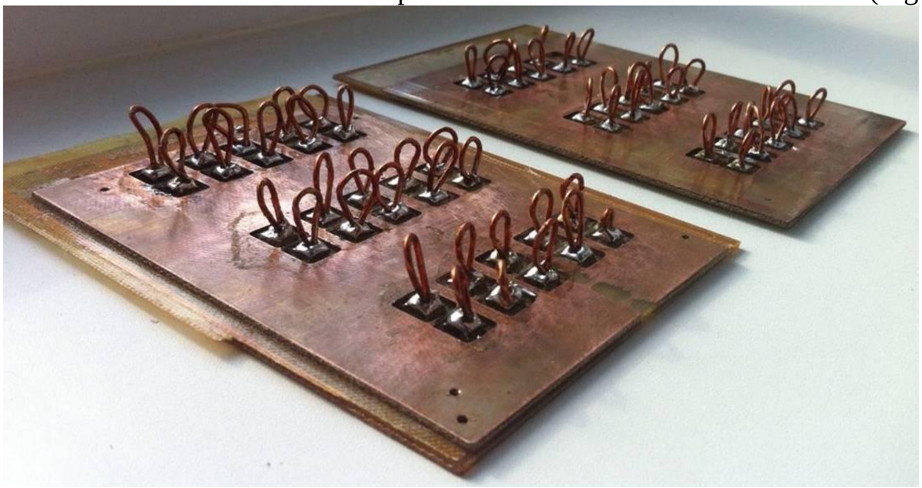


Figure 6. Test samples assembled

Hooks for detaching samples from the base are made of wire with a cross-section of 2.5 mm. The hooks are fixed using a solder joint, which simulates the real soldering process during the manufacturing of modules on PCB. The tests were carried out on the Instron 3345 tensile testing machine. The average values of the measurement results are summarised in Table 1.

Table 1. Average measurement results

| Mask | Grid, N | Zone without foil, N | Zone with solid foil, N |
|---|---|---|---|
| Solid 60 µm | 90.6 | 94.7 | 87.5 |
| Solid 90 µm | 91.2 | 97.6 | 88.3 |
| Mesh 60 µm | 88.2 | 90.5 | 85.9 |
| Mesh 90 µm | 89.4 | 93.1 | 87.4 |
| Prepreg | 94.2 | 98.3 | 89.8 |
| Prepreg + solid 60 µm | 90.8 | 94.5 | 87.4 |

*Experiment 2. The method of applying the cross-cuts.* The essence of the method is to apply at least three parallel scratches with a distance between them from 2 to 3 mm and perpendicular to them also at least three parallel drawings with the tip of the cutter. The cuts are applied in one direction with a depth up to the base metal. The hardness of the tip material should be higher than the hardness of the coating. After scratching, there must be no flaking of the coating between the lines and in the grid of squares (Figure 7). The results are assessed according to Table 2 [23].

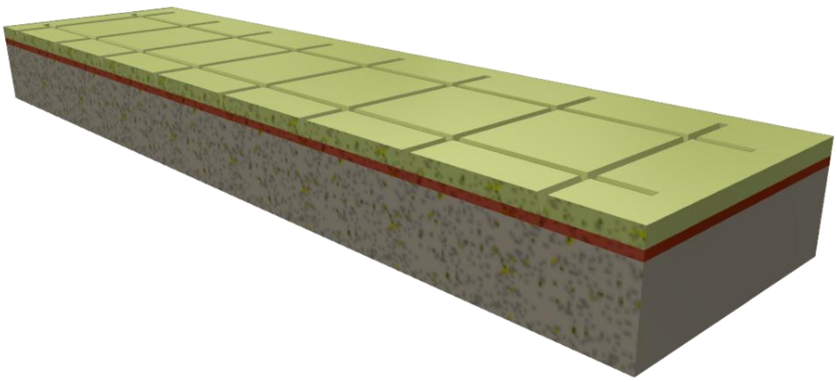
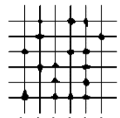
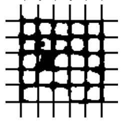
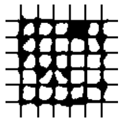
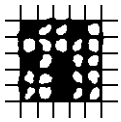


Figure 7. The sectional view of the sample model for the cross-cut test

Table 2. Classification of test results

| Classification | Description | The appearance of the surface of the cross-cut area from which flaking has occurred (Example for six parallel cuts) |
|---|---|---|
| 0 | The edges of the cuts are completely smooth; none of the squares of the lattice is detached. | – |
| 1 | Detachment of small flakes of the coating at the intersections of the cuts. A cross-cut area not greater than 5% is affected. |  |
| 2 | The coating has flaked along the edges and/or at the intersections of the cuts. A cross-cut area greater than 5% but not greater than 15% is affected. |  |
| 3 | The coating has flaked along the edges of the cuts partly or wholly in large ribbons, and/or it has flaked partly or wholly on different parts of the squares. A cross-cut area greater than 15% but not greater than 35% is affected. |  |
| 4 | The coating has flaked along the edges of the cuts in large ribbons and/or some squares have detached partly or wholly. A cross-cut area greater than 35% but not greater than 65% is affected. |  |
| 5 | Any degree of flaking that cannot even be classified by classification 4. | – |

For the experiment, six samples were made with a 3D soldering mask with a thickness of 16, 30, 45 µm. As in the case of the breaking load test experiment, samples are made of pure fiberglass laminate, solid foil, and a diagonal grid of 1 mm wide conductors spaced 4 mm apart. Each sample is designed to conduct 1 experiment. In total, 18 experiments (9 combinations) were conducted. A steel blade was used to apply the cross-cuts (Figures 5 and 6).

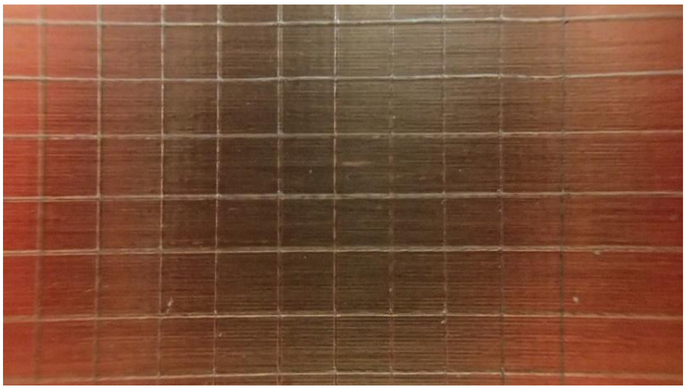


Figure 8. Cross-cut, copper base

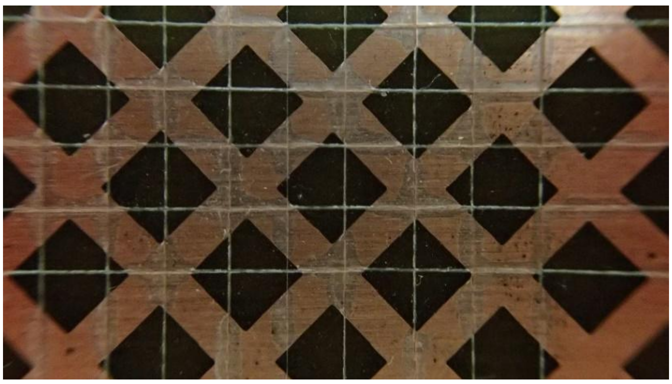


Figure 9. Cross-cut, combined base

*Experiment 3. The sticky tape method.* Sticky tape tests are performed by applying the tape with the adhesive side to the test sample with a cured coating applied. The presence of air bubbles and debris particles between the applied adhesive tape and the sample surface is not allowed. The test area is not less than 1 $cm^2$. The tape is separated from the sample after 10 seconds by applying a constant force perpendicular to the surface of the test sample. The results are assessed by visual inspection using an optical device that provides $3^x$ magnification (Figure 10).

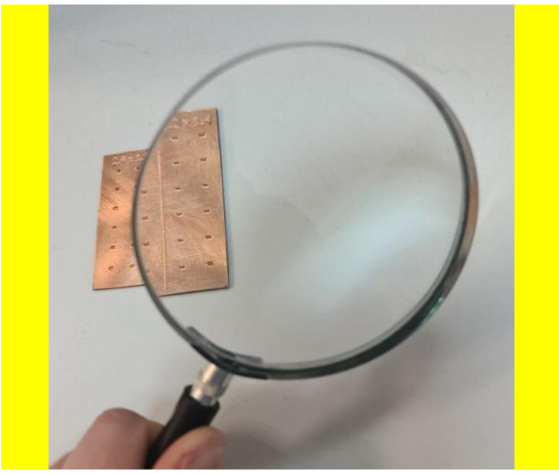


Figure 10. Inspection of samples after the experiment with sticky tape

As in previous experiments, three types of similar samples were studied (pure fiberglass laminate, solid foil, and a diagonal grid of conductors). Ten samples of each type were tested. To ensure a constant effort when tearing off the adhesive tape and eliminating the human factor, a tensile testing machine from experiment 1 was used.

## 4. Conclusion

The results of the breaking load experiments indicate that 3D masks show comparable separation forces with a prepreg. At the same time, the force is stable for all types of surfaces and practically does not depend on the thickness and configuration of the 3D mask. Experiments with applying cross-cuts show consistently good results with a homogeneous base material – there are no coating detachments. In the case of using a combined base (fiberglass/copper – imitation of printed conductors), the appearance of coating detachments is observed in the case of risk passing through the boundary of the base materials. In this experiment, the samples scored from 0 to 2 points on a 6-point scale (less is better). The presence of the defect is explained by the presence of a "step" between the base materials and can be compensated in the process of further research. The adhesion test in the 3rd experiment showed a consistently good result: there are no swellings, delaminations, violations of the coating integrity. In addition, in the case of using this type of soldering mask, it is possible to influence the adhesion of such factors as the temperature conditions of soldering and the interaction of the 3D soldering mask with fluxes, which requires additional research. In addition, it is necessary to check the preservation of the properties of 3D soldering masks during operation, which would require conducting climatic and other types of tests.

Thus, it can be concluded that the use of 3D soldering masks on the inner layers of multilayer printed circuit boards with built-in components is possible, but a number of issues must be solved for this, including those related to the software for generating 3D mask structures. It is necessary to continue research and study the behavior of solder masks not only with respect to the base but also with respect to the components, to establish the presence and nature of solder leakage under the mask, to evaluate the accuracy of applying masks, to search for their optimal configuration, etc.

**Acknowledgments**

The research was carried out within the state assignment of the Ministry of Science and Higher Education of the Russian Federation (theme No. FSFF-2020-0015). The authors would like to thank the editor and anonymous reviewers for their comments that have helped to improve the quality of this paper.

**References**


[1] M. Sokolsky and A. Sokolsky, “Electrochemical Migration: Stages and Prevention,” *Amazonia Investiga*, vol. 8, no. 22, pp. 757-765, 2019.

[2] F. Vasilyev and A. Medvedev, “Detection of Hidden Interconnect Defects,” *Electronics: Science, Technology, Business*, vol. 10, pp. 94-97, 2018. https://doi.org/10.22184/1992-4178.2018.181.10.94.97

[3] E. Beger, “Soldering Mask: Features of Design and Manufacture,” *Electronics: Science, Technology, Business*, vol. 3, pp. 94-98, 2009.

[4] C. X. F. Lam, X. M. Moa, S. H. Teoha and D. W. Hutmacher, “Scaffold Development Using 3D Printing with a Starch-Based Polymer,” *Materials Science and Engineering: C*, vol. 20, no. 1-2, pp. 49-56, 2002.

[5] Y. Yang, Y. Chen, Y. Wei and Y. Li, “3D Printing of Shape Memory Polymer for Functional Part Fabrication,” *International Journal of Advanced Manufacturing Technology*, vol. 84, no. 9-12, pp. 2079-2095, 2016.

[6] P. G. McMenamin, M. R. Quayle, C. R. McHenry and J. W. Adams, “The Production of Anatomical Teaching Resources Using Three- Dimensional (3D) Printing Technology,” *Anatomical Sciences Education*, vol. 7, no. 6, pp. 479-486, 2014.

[7] D. Levashkin, P. Ogin and F. Vasilyev, “Efficiency of Hybrid Cyclic Processing with the Use of Additive Technologies on CNC Machines for the Manufacture of Composite Aviation Parts Due to the Reduction of Processing Errors,” *Materials Science Forum*, vol. 946, pp. 959-965, 2019.

[8] A. Ripetskiy, T. Mirolyubova and S. Freylekhman, “Analysis of Factors That Determine the Possibility for Automation of Smoothing of Product Electronic Model, Obtained Through Topological Optimization for the Purpose of Its Use in The Technological Preparation of Additive Manufacturing,” *Periódico Tchê Química*, vol. 15, no. 1, pp. 405-413, 2018.

[9] A. O. Gorelov, “Applying Solder Masks on a 3D Printer,” in *Moscow Youth Scientific and Practical Conference “Innovations in Aviation and Cosmonautics – 2014,”* Moscow: Moscow Aviation Institute, 2014.

[10] F. V. Vasilyev and A. O. Gorelov, “Adhesion of Solder Masks Obtained on a 3D Printer,” *Electronics: Science, Technology, Business*, vol. 6, pp. 194-196, 2017.

[11] W. Jillek and W. K. C. Yung, “Embedded Components in Printed Circuit Boards: A Processing Technology Review,” *International Journal of Advanced Manufacturing Technology*, vol. 25, no. 3-4, pp. 350-360, 2005.

[12] A. Nissan, “Embedding Passive and Active Components in Printed Circuit Boards – An Alternative to Printed Wiring,” *Electronics: Science, Technology, Business*, vol. 6, pp. 86-92, 2011.

[13] Qualification Requirements KT-160D. 2004. https://rfimmunity.com/wp-content/uploads/2017/04/KT_I60D_RTCA_Russian.pdf.

[14] T. Ferguson and J. Qu, “Effect of Moisture on the Interfacial Adhesion of the Underfill/Solder Mask Interface,” *Journal of Electronic Packaging*, vol. 124, no. 2, pp. 106-110, 2002.

[15] A. Ripetskiy, “Polygonal Meshes Data Structure Analysis Used for Computation of the Parameters Defining Additive Production Process for Different Additive Manufacturing Technologies,” *Periódico Tchê Química*, vol. 15, no. 1, pp. 291-303, 2018.

[16] A. A. Orekhov, A. V. Riprtskiy and D. V. Fedoseyev, “Surface Roughness Assessment Based on Discrete Model Representation for Additive Manufactured Parts,” *Periódico Tchê Química*, vol. 15, no. 1, pp. 514-524, 2018.

[17] F. V. Vasilyev and A. O. Gorelov, “The Use of Soldering 3D Masks on the Inner Layers of the WFP with Built-In Components,” in *Proceedings of the XXV International Scientific and Technical Conference “Modern technologies in control, automation and information processing,”* Moscow: Moscow Aviation Institute, 2016.

[18] A. Ripetskiy, S. Zelenov and L. Rabinskiy, “Evaluation of the Thermal Processes and Simulation Methods for Additive Manufacturing Based on the Geometry Voxel Representation,” *Key Engineering Materials*, vol. 771, pp. 91-96, 2018.

[19] S. Vantsov, F. Vasilyev, A. Medvedev and O. Khomutskaya, “Quasi-Determinate Model of Thermal Phenomena in Drilling Laminates,” *Russian Engineering Research*, vol. 38, pp. 1074-1076, 2018. https://doi.org/10.3103/S1068798X18120316

[20] A. Ripetskiy, S. Vassilyev, S. Zelenov and E. Kuznetsova, “Current Issues of Developing Methodology and Software Solutions Used in Different Phases of Modelling Additive Production Processes,” *Key Engineering Materials*, vol. 771, pp. 97-102, 2018.

[21] K. Z. Khairnasov, “Mathematical Modeling of Shell Configurations Made of Homogeneous and Composite Materials Experiencing Intensive Short Actions and Large Displacements,” *Journal of Physics: Conference Series*, vol. 991, no. 1, article number 012043, 2018. https://doi.org/10.1088/1742-6596/991/1/012043

[22] IPC-TM-650, Method 2.4.28.1. 2021. https://www.ipc.org/test-methods.

[23] ISO 2409:2020 Paints and varnishes — Cross-cut test. https://www.iso.org/ru/standard/76041.html