Influence of the 3D Model and Technological Parameters on the Mechanical Properties of Fused Deposition Modeling 3D Products

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***Abstract*—Additive technologies represent a broad portfolio of methods and procedures for achieving the desired product properties by adding materials. The original meaning of visualization and testing of spatial properties in assemblies is enhanced by requirements for functional properties. The use of the engineering component created by the additive technology depends primarily on the mechanical properties that directly determine the function of the component in the assembly or separately. In this paper, we present the results of research on the mechanical properties of three-dimensional (3D) print materials, depending on methods for the creation and analysis of 3D models and selected technological parameters of printing by a Fused Deposition Modeling (FDM) method. This is a printing method based on the application of polymeric materials in a viscous state in layers. These are technologies with affordable equipment, materials, and print progress. Results are obtained by standardized measurements of acrylonitrile butadiene styrene print samples, which is considered the default FDM 3D print material.**

***Index Terms*—additive technology, computer-aided design, computer-aided engineering, digital model, fused deposition modeling, rapid prototyping.**

I. Introduction

Three-dimensional (3D) printing represents a group of printing production methods including applying or changing the structure of the material. Because the material is added, it is an additive technology. The Fused Deposition Modeling (FDM) method is based on the deposition of molten plastic in the form of fibers of a certain thickness into layers. The geometric starting point is a digital 3D volume model, created in a computer-aided design (CAD) tool [1]. The applied material is usually plastic or a composite with a significant proportion of the plastic matrix. We cannot expect the same characteristics with the starting material in terms of mechanical properties, but there are many industries where parts produced by FDM basic methods have sufficient characteristics for use with expected properties. Besides mechanical properties, dimensional and shape accuracy is an important parameter. The above-listed parameters are crucial for secure positioning of components in the assembly and subsequent corresponding functions, according to specifications. The desired degree of accuracy depends on the expected operating parameters of assemblies, usually depending on the sector. The declared printing precision of simple 3D printers using FDM (e.g., for engineering) is relatively low. It is affected by some technological and material parameters [2]. Particularly in the case of miniature machinery parts, the printing accuracy achieved directly affects the usability of a part. Print settings in preparation for producing a component may not represent a reliable way to achieve results. Another option is direct intervention in the original model, presenting this adjustment [3]. The obtained result is hence a combination of model editing and postprocessing data [4].

II. Fused Deposition Modeling Related Principles

The principle of the method is the application of plastic materials in thin layers. The material is extruded from the nozzle and constitutes a fiber having a defined thickness and viscosity. The layer's thickness is determined by the vertical displacement of the nozzle step *z*-axis, which continuously moves in a 2D plane of the layer along the direction of the vector specified by the components in the *x*- and *y*-axes [5]. First, a base layer is deposited on the substrate, which is usually due to the nature of the material heated to a specific temperature. In the basic configuration, the printer is equipped with a feeding device with a single head. It is desirable that component printing takes place in a single cycle, especially by the open print area of the printer where it is necessary to take account of the process of cooling the printed sample, depending on the size and complexity. The coating of only one axis represents a limiting factor in complex products for printing overhanging surfaces. When exceeding the overhang limit, successive layers of the product can be realized only by parallel printing of supports in previous layers. Other limiting factors are the diameter of the nozzle and the associated dimensional accuracy, surface quality, and miniaturized components' overall manufacturability [6].

III. Preprocessing of Data for 3D Printing

The initial geometry is represented by CAD data describing the shapes and dimensions of the part model,

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the virtual prototype [7]. The primary factor is the component function from a structural standpoint, from which the shape, dimensions, and appropriate precision are derived. Part manufacturability by the related production technology can be considered as a secondary factor. Complex-shaped parts were produced by machining—manual, mechanical, or a combination of both—before the start of 3D printing. Later generations of machining represented multi-axis computer-controlled machines, where a complex shape is achieved by moving of the tool on 2D or 3D trajectory. Limitations of a shape are given especially by the shape of the instrument and its size in context with the cutting forces, the rigidity of the system, and the desired productivity. A component is produced directly by that method, or a shaped tool for casting or molding is produced. The FDM 3D printing method represents an additive technology, where the material is added by the specified method.

The shape of the tool represents a nozzle, which is the final element of the system of production equipment. The material is applied in the form of fibers having a thickness corresponding to the diameter of the nozzle. The layer's thickness is determined by the movement of the nozzle in the direction of a main axis, usually a vertical axis, *z*-axis.

The principle of applying materials in layers determines the achievable complexity of the component shape. This is one of the factors limiting the workability of a component. Similarly, as in the limitation of the bevels of mold cavities for casting, in this case, the critical parameter is an overhang of a part shape without a support. When modeling a component or modifying a model, it is one of the first monitored factors. Analysis of the draft angles and decision on a possible change in the shape or printing supports while printing the main product can be carried out within the basic diagnostic tools. Supports represent an additional print material, extend the printing time, and can impair the surface quality of components at junctions. In some cases, it is however necessary to assess the difficulty of separating the support from the component, especially in the case of removal from the cavity. A partly related factor is the limitation of part dimensions by printable envelopes specified by the printer parameters. A component model is usually modeled in a 3D Cartesian coordinate system *x*-*y*-*z* and the data is exported into the appropriate format for postprocessing, which usually respects the absolute coordinate system. The preferred step is the orientation of a large model with respect to the coordinate system of the printer and the size of the print area, taking account of the overhangs and the assessment of support printing. The default parameter for achieving molded details of small dimensions is to use a nozzle with a small diameter when preparing shaped models with small details (e.g., gears with small modules). The result is hence the extension of the press, but with a reliable result.

The procedure is analogous to the tool correction for preparing and editing the NC machining program [8]. Print restriction can be eliminated to some extent by adjusting the geometry according to the dimensions of the fibers of the extruded material. This is a significant manual effort, where the key is the empirical findings of the system behavior when printing a specific shape.

An example of original geometry without a correction for the size of the fibers in the nozzle is shown in Fig. 1.

The example is demonstrated on a gear with a module of 0.5, and the overall height of the tooth is thus 1.25 mm. The simulation is shown in the postprocessor. Without a correction, the teeth are not printed in a sufficient accuracy.

The correction in the model within the preprocessing is enabled by a given parameter in jet toothing printing precision, allowing reliable engagement and performance features in an assembly. A corrected wheel is shown on the postprocessor in Fig. 2.

When changing the nozzle to 0.25 mm, the postprocessor simulation already provides the result in acceptable limits without model correction [9]. This is the ideal case, and the procedure is best suited for the printing of small precision components.

The method of model correction is not feasible with limited technical capabilities. Problems are shape details printed on larger component, where the primary use of small jets would lead to the extension of the fold printing. An example of an accurate wheel with a combination of model correction and the diameter of the fiber material, depending on the nozzle in postprocessor, is shown in Fig. 3.

Verification of the strength and elasticity characteristics of a component through appropriate CAE-FEM simulation and subsequent analysis of simulation is integral to model preprocessing [10].

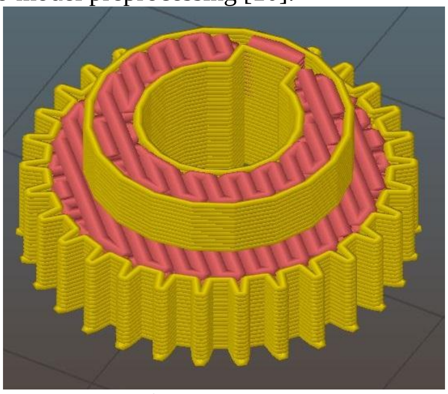

Figure 1. The achievement of the required accuracy by the correction of the nozzle diameter, fiber.

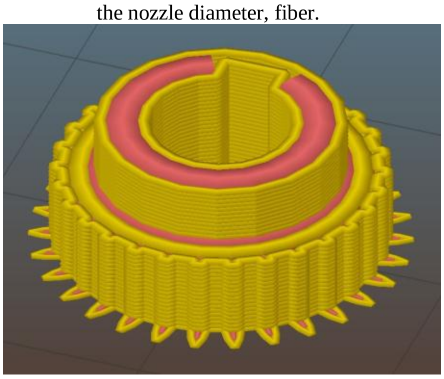

Figure 2. Problem in achieving the desired accuracy without correction on the nozzle diameter.

The strength characteristics in addition to the structural material properties are determined by the type of the filler body component, where this parameter can be relative to the size of the model to implement. A suitable filler systemically describing the characteristics of the structural elements with a honeycomb-shaped structure is shown in the postprocessor (Fig. 4).

A structural honeycomb is generated by postprocessing according to the volume of the model and the density of the fill.

For the purposes of simulation and analysis and to accurately assess the effect of the filler on the mechanical properties of the construction, it is advantageous for preprocessing to create a parametric universal pattern. An example of a universal forming pattern with the representation of the envelope of a profile is shown in Fig. 5, as well as a trimmed filler in Fig. 6 and a compact body shell of a wing having a defined filling in Fig. 7.

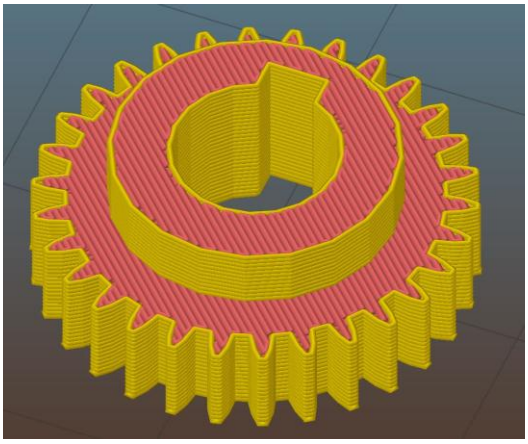

Figure 3. Achieving a precise shape and size by reducing the diameter of the nozzle and model correction.

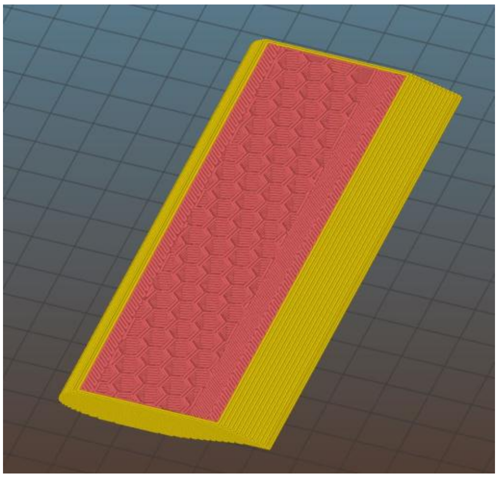

Figure 4. Postprocessing of 3D printing of the model with a structural honeycomb filling.

The results of CAE-FEM simulations are shown in Figs. 8 and 9. The simulation was performed for the following two types of fill:

- No fill only shell (Fig. 8).
- Honeycomb with 50% density (Fig. 9). That methodology can be implemented for any part shape. An example is provided on a model of a wing with a rectangular floor plan and a laminar profile (NASA GAW-2).

The constraints of the simulation are set according to the aircraft wing behavior model of the airplane loaded in flight. For simplicity, insertion at the points of connection to the centerline is considered (the removal of all six degrees of freedom at the point of the root of the wing). The load is set according to the layout on the top and bottom of the profile surface. The results of the deformations for the same material and the same temperature program are shown in the figures, with the material parameters corresponding to the best results of the characterization obtained by the tensile, bending, and impact tests as shown in the graph of Fig. 10 in Chapter V. Under the same constraints, a progressive reduction in element stress in the honeycomb with a 10% fill over a simple shell can be identified.

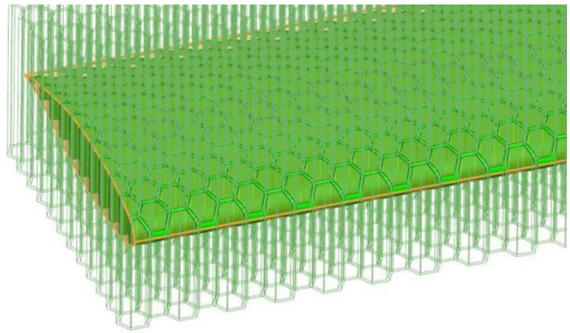

Figure 5. Preparation for CAE of the model and FEM simulation filled with honeycomb design for use on different profiles.

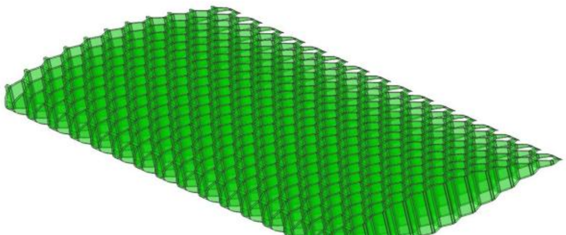

Figure 6. Honeycomb design for CAE-FEM simulation and application on NASA GAW-2.

The simulation results for the full material (100% fill) are rather informative because there is a more significant weight increase than the progress of the bending stress reduction in the shell elements and the partial fill.

IV. Postprocessing of Data for Rapid Prototyping

Technological printing parameters are set when creating and debugging the postprocessor. The preprocessed model can be at this stage subsequently oriented to the principal axes of the printing system. It is preferable to solve orientation within the preprocessing in a CAD tool with the support of appropriate diagnostic tools and handling techniques. Postprocessing represents a technological stage where the technological printing conditions are specified on basis of a model shape, the required accuracy, the printer parameters, and the material properties. Some parameters are specified with the possibility of manual correction during printing. The fixed parameters are the material properties and the method of material flow. Determining the optimal parameters is the solution to the multidimensional optimization problem. The primary factors are the shape and the complexity of the model, determining the position of the body during printing, and considering the need for body distribution. The FDM printing method uses materials based on polymers, and there are no expectations about significant strength characteristics by the produced parts. Thus, complex models can combine multiple parts, usually by bonding. Adequate products must be determined for bonding of polymeric materials, for etching contact surfaces, and for subsequent diffusion. In case of materials based on natural products, multicomponent adhesives can be used. Joining parts is a solution with utmost importance; its main goal is to achieve a compact press model without division.

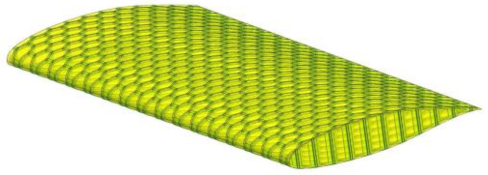

Figure 7. The final model with honeycomb.

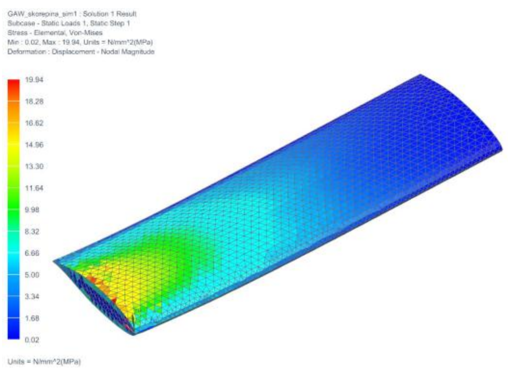

Figure 8. Shell body analysis, with a simulated force on the wing.

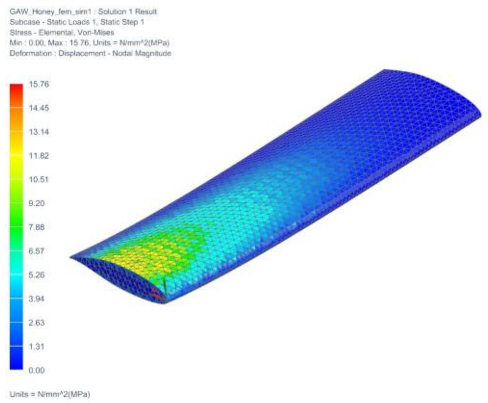

Figure 9. Honeycomb fill body force simulation.

The subsequent factors are the desired accuracy and surface quality. Accuracy directly affects the use of the nozzle diameter, which is inversely proportional to productivity.

The key factor of postprocessing is to determine the material and the related mechanical and especially technological properties. The primary material-technological parameter is the melting temperature of the material in the nozzle, affecting the quality of the applied fibers and joining with the already deposited material.

The functional, mechanical, and technological properties of the final model are primarily determined by the material and secondarily by the used technology.

Acrylonitrile butadiene styrene (ABS) was chosen as the FDM printing material. It is a thermoplastic copolymer used in the industry. The declared material properties include mechanical properties, usually corresponding to the starting table value. There are some variations in the same material from different manufacturers. Data tabulated in the data sheets are not always reliable. The mechanical tests verify the accuracy of the data. Transforming the starting material in the plastic state into the fiber diameter according to the applied nozzle is carried out when applying layers of the printed sample, in a range of diameters: 0.25, 0.4, 0.5, and 0.6 mm. Standard productive printing is carried out with a nozzle diameter of 0.5 mm. 0,25 mm nozzle is used to print the products of the highest quality. The mechanical properties of the printed sample volume of the body are determined by the following characteristics: consistency of the deformed fibers, material changes due to heating, bonding of the fibers with the previous layer, bonding of the fibers within one layer, and mutual fiber configuration in volume.

Deterioration of the mechanical properties of the finished print product, compared with the theoretical properties considering a starting compact material, can be assumed. The factors that affect the mechanical properties of the product are determined by the following parameters: the number of layers of the shell, direction of the fiber fill, density of fillings, and the fill type.

The anisotropy of strength, just like with fibrous composites with differently oriented fibers in layers, can be expected. In the preparation of the experimental samples, to determine these characteristics, it is necessary to respect the parameters listed in the list, the combinations thereof. The target is to find the compromise between mechanical and technological properties. In industrial printing, it is also necessary to consider the factor productivity. The FEM simulation parameters for the ABS material with structural properties based on a specific 3D printing method are obtained by a tensile and bending test. The input parameter is the temperature program that affects the properties of the material after printing, the bonding of the fibers, and the shape stability. The input parameters obtained by standard methods of measuring are shown in the graph of Fig. 11. The best strength and elastic properties can be identified on the graph by the nozzle temperature of 280 ℃. Results are obtained by experimental measurements when the print string producer states an optimal print temperature of 260 ℃. To prepare product printing, where an emphasis is placed on strength and elastic characteristics, it is a good idea to import the experiment's results as material parameters into the FEM tool for simulating and optimizing the CAD model.

V. FDM Printed Materials' Mechanical Properties and Experimental Results

ABS materials are used in a wide range of applications in the industry. These materials are suitable for many other manufacturing methods, for example, in injection molding, in blow molding, in extrusion, and as a filament for 3D printing products [11].

ABS materials have been tested by MFI measurement for characterization of viscosity, melt flow index, and others. ABS were characterized by MFI measurement. The average mass flow rate was 17.779 g/10 min, with a standard deviation of 0.310 g/10 min. The average volume flow rate was 17.095 cm^3/10 min, with a standard deviation of 0.298 cm^3/10 min. We determined rheological data such as the shear rate, shear stress, and viscosity. The shear rate was 31.562 s^{-1}, the shear stress was 89,631 Pa, and the viscosity was 2,839.821 Pa. We have chosen the following temperatures of the die for testing the ABS material using 3D printing at 285 ℃ by these parameters.

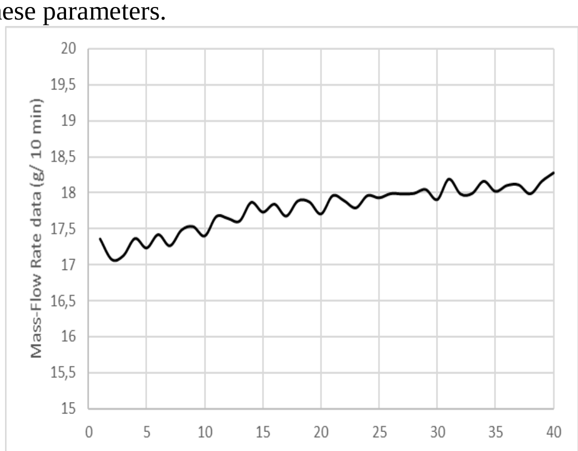

Figure 10. Mass flow rate data during measurement.

ABS materials have been tested to characterize mechanical properties using an Instron 3345 machine before 3D printing. The ABS material had a modulus of elasticity of 1,227.8 MPa, with a maximum load of 224.2 N. 3D printing models with different internal structures were tested using bending and tensile testing. The test results can be seen in Tables I and II. The best bending test results were shown by the model full block with a maximum load of 1,319.7 N, a bending extension of 1.2 mm, and a bending stress of 60.2 MPa at the maximum load. Results for the same internal structures (full, empty, or honeycomb) are different for the models (block versus final model). Similar conclusions can be drawn for model testing using tensile testing.

TABLE I. Results of the Bending test.

Kind of model	Max. load (N)	Bending extension at maximum load (mm)	Bending stress at maximum load (MPa)
Full block	1319.7	1.2	60.2
Empty block	214.8	1.5	9.8
Honeycomb block	603.6	1.2	27.5
Full final model	1116.6	1.4	50.9
Empty final model	88.8	5.9	4.0

TABLE II. Results of the Tensile Test.

Kind of model	Max. load (N)	Tensile stress at maximum load (MPa)	Modulus of elasticity (MPa)
Full block	4680.9	15.0	222.9
Empty block	736.2	3.9	92.6
Honeycomb block	2101.9	7.9	130.9
Full final model	4898.1	16.2	235.6
Empty final model	1160.9	7.7	179.8

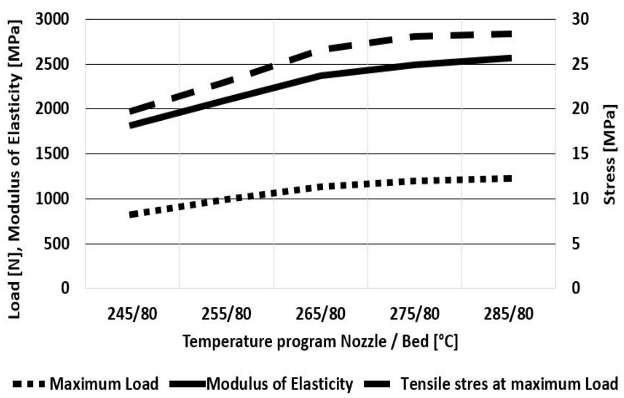

Figure 11. Stress and elasticity analysis on real ABS materials, provided with an FDM 3D printing method by a temperature program.

VI. Conclusion

The primary factor for effective 3D printing of complex models with simple FDM methods is a coherent digital model created in CAD. The consistency of the model is the compactness of boundary surfaces and edges of a solid body. The orientation of the model relative to the coordinate system of the printer and using self-printed supports can be diagnosed in the phase of postprocessing based on the analysis of the shape during model creation. The aim is to avoid printing supports by an appropriate orientation of the model. The orientation of the model relative to the coordinate system of the printer has an impact on the internal structure of the product, which affects the functional mechanical properties of the printed components in different directions, caused by the anisotropy of the resulting material structures. An important step for printing the shape details of small dimensions with a desired accuracy and surface quality is to adjust the model. The shape correction is based on fiber size, which is particularly important when using larger-diameter nozzles. An important factor for printing functional parts with the requirements for strength and an acceptable level of deformation is the material structural property. The difference in the structure of the print volume compared to the starting material is a significant factor. Before the production of a functional component we use a CAE simulation for verification of strength and elasticity characteristics. Individual variants of material structures, depending on the set printing technology, are certified by the relevant tests. Results are imported into CAE tools. Improvement of mechanical properties can be achieved by the development of new print materials. Particulate composites of the polymer matrix are a prerequisite for efficient printing because of the characteristics of printing by FDM. The development of new printing materials is also related to the development of printing facilities and new or innovative printing methods. The default material for printing on simple printers using the FDM method is usually a string. The material feed is mechanically synchronized with the feed rate of the nozzle. Printing functional components typically involves rigid or low-resilience bodies. The printing of elastic components requires materials that are difficult to feed in the form of a string, because of their original and subsequent postprinting viscosity. In these cases, a special feeder of viscous materials can be used, the flow of which to the nozzle is synchronized electromechanically through the device's control unit. The methodology of CAD modeling, production technology preparation, and product testing is also applicable to the research of functional and technological features of 3D printing components produced by other 3D printing methods, such as SLS-DMLS, SLA, and EBM. As with polymeric materials, metallic materials are assumed to have slightly different properties relative to the starting material. The rules for creating a 3D CAD model are the same. Creating a CAD model is independent of tool used. CAD procedures are based on basic modeling procedures or customary free-forming methods. Common modeling tools allow the export to one of the universal formats for eventual editing in another tool or for processing in the development of technology. Postprocessing in these cases is dependent on the applied printing technology. For preprocessing with a CAE tool, especially the simulation of structural properties, model details can be used. In all cases, simulation is primarily implemented in FEM tools using the table properties of the starting material. Only after the samples have been printed and the relevant experimental measurements are made can the values be adjusted and a FEM recalculation be carried out with the same boundary conditions used in the initial simulation performed. The preprocessing and postprocessing of the model using CAD and CAE tools is very efficient. This advantage is particularly evident when testing samples with final shape and dimensional characteristics. Pairing of models allows producing a fixture with the appropriate shape and dimensional accuracy, which ensures adequate measurement accuracy during the experiment phase. The subject of subsequent experiments is also the research on the anisotropy of 3D print material after FDM printing. Anisotropy research is based on the fiber characteristics of the print volume, and the influence of the fiber arrangement is expected to be in both the full material and the specified partial fill. A prerequisite is the analogy of fibrous structural composite materials based on glass, carbon, and polymeric fibers. The interconnection of the physical component and the test preparation can be analogous to mold-based tool production or soft pressing. The easy molding of the CAD model and the subsequent creation of a formally complex cavity of molds of the corresponding quality parameters allow the formation of cavities and inlet systems for the casting of viscous materials. The chemical properties of polymer materials allow a wide range of surface treatments. They may be varnished or directly etched to provide a thin shell to support the mechanical properties of the resulting printing component. Research on the technological parameters of 3D FDM printing is realized within the range of parameters available on most printing devices. The preprocessing and postprocessing technologies are fully portable between different devices and are applicable across all disciplines that can use component and assembly creation with available 3D printing.

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