Use of Methods and Technologies of Additive Production for Optimization of Parameters of Designs

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Abstract. The article presents the existing methods of implementation of rapid prototyping technologies in rapid production. It is performed using computer modeling programs with integrated modules of generative design based on different topology optimization methods. In the environment of ANSYS Mechanical (Workbench) the finite element method established the dependence of strength parameters on the density of the generated mesh of the reinforcing contour of the part. According to the results of the simulation, the graphical dependencies of the maximum general stresses and the margin of safety of the part depending on the materials of the 3D models under the action of equivalent stresses were obtained.

1. Introduction.

The rapid development of scientific and technological progress requires any large and small series production to be constantly and timely updated and keep up with the times, as today's industry requires the use of newer and more advanced production technologies focused on the widespread implementation of robotic systems to control all production processes.

In turn, the gradual improvement and modernization of production require the use of more modern design methods and materials [1-3] to increase the durability and ergonomics of products. As a result, it requires the use of state-of-the-art production methods, one of which is the rapid prototyping technology of Industry 4.0 [4], which, unlike traditional production technologies, allows us to design and manufacture a production facility in the shortest possible time. Also with the help of modern methods of computer modeling, it is possible to identify weaknesses and imperfections of the structure directly at the stage of their design in terms of strength and durability (additive production) figure 1.

\textbf{Figure 1.} Scheme of the production process of detail development
Creating a 3D model or its reengineering is done in several common ways, including the use of a 3D scanner that analyzes the physical object and based on the obtained data creates a 3D model of the design object mostly in formats (STL, OBJ, PLY, WRL). The advantages of the 3D scanner are that in a relatively short time you can get an exact copy of the object (model), which is further refined in computer 3D graphics programs (Autodesk Inventor, DS SolidWorks, DS CATIA, Ascon Kompas-3D, Siemens NX, and others).

Also, to create a new, more original or improved model, computer modeling programs are used, which contain integrated modules of engineering calculation, analysis, and simulation of physical processes (FEA module) performance of the design object (dynamic simulation). As well as possible optimization of parameters of detail by mass and shape using modules shape generator, topology study, and generative design figure 2 without significantly reducing its strength characteristics [5, 6].

![Figure 2. The ways of optimization of models by shape and mass:](image)

To optimize the parameters of the structure and reduce its material consumption quite often there is a need to create a hollow object of complex shape, the manufacture of which on CNC machines is quite a difficult task, and sometimes impossible.

Quite often casting is used as the means of manufacturing of parts, which allows getting parts of good quality using a small amount of material. However, this method is more efficient for mass production of parts of simple shape. There are also increased requirements for the technology of manufacturing parts, as due to casting under pressure of composite materials there are various defects [7].

Also, one of the promising methods of making an object based on previously created triangulated models is its printing (growing) on a 3D printer. In turn, the technology of the production of ultra-complex elements of parts is most likely to be made by one of the technologies of 3D printing.

2. Statement of the problem

In the era of development and implementation of industry 4.0 technologies, one of the priority areas of which is 3D printing, there is a gradual requirement for the use of heterogeneous materials to create authentic and original parts by purpose and form. In particular, the technology of laser 3D printing of powder and photopolymer materials (SLM, SLS, SLA, DMT, DMD) is one of the most promising but expensive technologies. Nevertheless, 3D printing technologies of various composite materials, such as FDM, MJM, PolyJet, CJP, have become widespread. As a result, the implementation of additive production technologies allows the development of this area due to the inclusion in the plastic materials' different physical and mechanical properties, resulting in an increased melting point and, accordingly, fatigue strength characteristics of the products [4].

However, the use of various types of reinforcing materials in the plastic structure leads to rapid wearout or violation of the geometry of the printing brass nozzle, which in turn affects the accuracy (precision) of the obtained parts. The use of a nozzle made of a harder material reduces its thermal conductivity, which negatively affects the flow of the filament.

Therefore, to increase the fatigue strength characteristics of parts made of various composite materials, it is advisable to strengthen them. However, the creation of a solid frame of the part helps to
increase the strength of the whole part but does not take into account the direct strengthening of the structure of the part in places of greatest stress concentration [8, 9].

Since, today in the technologies of three-dimensional CAD modeling and engineering calculation CAE systems have widely developed technologies of generated design and generative design, the use of which, at the stage of preparation of the model for 3D printing, makes it possible to generate a framework for the whole model or only its necessary part. The combination of generative design and design features of parts will help optimize their size-mass and fatigue-strength characteristics.

3. Methodology of research
To verify the adequacy of the described assumptions for parametric optimization, we use the ANSYS Mechanical (Workbench) software environment for engineering modeling and calculation of 3D models by the finite element method (figure 3, 4) [10-15].

![Figure 3. General view of the designed part model in ANSYS Mechanical (Workbench) environment](image1.png)

![Figure 4. Elements of the created design of the part model: a - designed 3D model; b - the generated frame of the 3D model.](image2.png)

Characteristics of the materials which are most frequently used for production details of 3D printing (see table 1).

### Table 1. The main characteristics of the used material

| Material    | Elasticity (Pa) | Poisson Ratio | Density (kg/m³) | Tensile Current | Yield Strength (MPa) | Minimum | Maximum |
|-------------|----------------|---------------|-----------------|-----------------|----------------------|---------|---------|
| ABS plastic | P 2.4E9        | 0.4           | 1050            | 36              | 30                   | 50      |         |
| AlSi10Mg    | A 7.1E10       | 0.33          | 2670            | 280             | 100                  | 320     |         |
| Steel 316L  | S 2E11         | 0.3           | 7550            | 230             | 185                  | 800     |         |
In order to research the connection between detail materials, geometrical parameters of the reinforcement frame figure 5, and strength indicators of a 3D model plan-matrix of experimental research was compiled (see table 2).

Figure 5. Dimensional parameters of the reinforcement frame:
a – diameter of the grid (d),
b – the distance between the horizontal elements of the grid in the longitudinal direction (L),
c – the distance between the horizontal elements of the grid in the transverse direction (W),
d – the distance between the vertical elements of the grid (H).

| Materials* | Base | Reinforcement | Geometric (mm) |
|------------|------|---------------|----------------|
|            |      | D  | L  | W  | H  |
| B          | P    | P  | 1  | 10 | 3  | 3  |
| C          | A    | A  | 1  | 10 | 3  | 3  |
| D          | S    | S  | 1  | 10 | 3  | 3  |
| E          | P    | A  | 1  | 10 | 3  | 3  |
| F          | P    | S  | 1  | 10 | 3  | 3  |
| G          | P    | A  | 0.5| 10 | 3  | 3  |
| H          | P    | A  | 1.5| 10 | 3  | 3  |
| I          | P    | A  | 1  | 5  | 3  | 3  |
| J          | P    | A  | 1  | 15 | 3  | 3  |

To study the details used a physical process that describes the equation (1) [10, 12]:

\[ \theta = \nabla \cdot s + F_v, \]

where \( F_v \) - the volume force vector [N/m³], \( S \) - the Piola-Kirchhoff stress tensor

The material of the model is considered linear elastic material, which is described by the equations

\[ \theta = \nabla \cdot s + F_v \]
\[ S = S_{ad} + \cdots + S_{el}, \quad C_{el} = C - C_{inel} \]
\[ C_{inel} = C_{el} + C_{ext} + C_{th} + C_{hs} + C_{pl} + C_{cr} + C_{vp} \]
\[ S_{ad} = S_{ad} + S_{el} + S_q \]
\[ C = \frac{1}{2} \left[ \left( \nabla u \right)^2 + \nabla u \right] \]
\[ C = C( E, \nu ) \]
We believe that the part is fixed on the inner side of the central hole (figure 6), i.e. on the specified surface the condition is met $u = 0$, where $u$ is a moving vector.

Figure 6. Rigidly fixed surface.

Also, the body is subjected to the gravitational force, as well as the force applied to the inner surfaces of the side holes (figure 7), which is described by equation

$$ S \cdot n = F_A $$

$$ F_A = \frac{F_{tot}}{A} $$

where $F_A$ - force per unit area [N/m²], $F_{tot}$ - total force [N], $A$ – area [m²]

Figure 7. Place of application of force.

Total force applied along the y component axis and is 1000 [N]. Mesh – Average Element size – from 0.5 to 1.5 mm, element type – solid, parabolic. The main parameters of the division into finite elements are given in the figure. 8

Figure 8. Partitioning into finite elements:
- a – designed 3D model
- b – generated frame of a 3D model
4. Simulation results
Based on the stationary and frequency research, the following simulation results are obtained, which are presented in figures 9-13.

**Figure 9.** The results of studies of total deformation
a - ABS, without reinforcement,
b - ABS Base, with aluminum reinforcement

As can be seen from figure 9, total deformation is three times smaller using a reinforcement frame.

**Figure 10.** Stress (Full construction):
a - ABS, without reinforcement,
b - ABS Base, with aluminum reinforcement

**Figure 11.** Stress (Base):
a - ABS, without reinforcement,
b - ABS Base, with aluminum reinforcement
Based on the research, a summary table of the results of the maximum stresses arising in the base material and reinforcement (see table 3).

Table 3. Maximum stresses that arise in the base material and reinforcement

| Base | Total deformation (mm) | Hot spot Stress HS (MPa) | Maximum General Stress GS(MPa) | Safety Factor (SF) | Hot spot Stress HS (MPa) | Maximum General Stress GS(MPa) | Safety Factor (SF) |
|------|------------------------|-------------------------|--------------------------------|-------------------|-------------------------|--------------------------------|-------------------|
| B    | 10,0                   | 236,5                   | 60                             | 0,7               | 232,7                   | 60                             | 0,7               |
| C    | 0,34                   | 241                     | 47                             | 6,3               | 241                     | 46,7                           | 6,3               |
| D    | 0,12                   | 237,9                   | 59,2                           | 4,2               | 244,4                   | 59,6                           | 4,2               |
| E    | 3,71                   | 179,5                   | 25                             | 1,44              | 2309                    | 540                            | 0,52              |
| F    | 2,17                   | 218                     | 14,1                           | 2,57              | 3629,7                  | 810                            | 0,28              |
| G    | 7,19                   | 272                     | 55                             | 0,66              | 3928                    | 940                            | 0,3               |
| H    | 2,0                    | 127,7                   | 15                             | 2,4               | 1636,5                  | 280                            | 1                 |
| I    | 3,18                   | 167                     | 9,9                            | 3,6               | 1330                    | 401                            | 0,7               |
| J    | 2,0                    | 127,7                   | 16,7                           | 2,15              | 1636,5                  | 310                            | 0,9               |
As we can see from the received research results of the interconnection between materials of a 3D model and geometrical parameters of a reinforcement frame, it was established that using a base model from ABS plastic, hot spot stress does not surpass 250 MPa, however, using ABS plastic with aluminum reinforcement, hot spot stress rises to 3928 MPa.

Conclusions
The use of computer-aided design systems and topological optimization modules makes it possible at the initial stage of modeling and development of parts to obtain their optimal parameters in accordance with the specified production conditions. Strengthening the structural parameters of parts made of composite materials by reinforcement, methods of generative design helps to increase their fatigue strength characteristics in places of greatest stress concentration.

Modern programs of topological optimization at this stage do not allow to optimize the parameters of parts of complex shape by reinforcement in the form of a regular structure with a combination of several materials. However, the process of parametric analysis and synthesis of bodies with a reinforcing mesh in the form of one of the regular structures can still be performed. Such a structure can create problems for automatic optimization, because changing the mesh parameters can change the number of bodies, as well as the configuration of the faces to which the boundary conditions are applied. Arbitrary exit of the reinforcement mesh outside to the surface of the part creates the possibility of the appearance of local concentrators (hot spots). The stress values in such concentrators are random values and in a linear formulation can reach huge value (which will not happen in reality due to the possibility of plastic deformation). Thus, when evaluating the solution to the optimization problem, it is recommended to evaluate not the level of maximum stresses, but the stresses at the control points of the structure and the general stress, which do not surpass 60 MPa for a basic model from ABS plastic. Using ABS plastic with aluminum alloy AlSi10Mg reinforcement stresses rise to 940 MPa. For these materials, the safety factor is 0.3 and 0.28. Maximum stresses for steel 316L are only 810 MPa, so they are a bit lower in comparison with aluminum alloy for the same dimensional parameters of the reinforcing mesh.

Since the melting point of steel is 1440 °C and of aluminum - 590°C, it is possible to use the latter as a reinforcing material in 3D printing technologies on state-of-the-art high temperature 3D printers.

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