Improving the printing process stability and the geometrical accuracy of the parts manufactured by the additive techniques

A I Borovkov¹, L B Maslov¹,², K S Ivanov¹, E N Kovaleva¹, F D Tarasenko¹ And M A Zhmaylo¹

¹Center of National Technological Initiative, Institute for Advanced Manufacturing Technologies, Peter the Great St. Petersburg Polytechnic University, 29 Politekhnicheskaya, St. Petersburg, 195251, Russia, E-mail address: zhmaylo@compmechlab.com
²Department of Theoretical and Applied Mechanics, Ivanovo State Power Engineering University, 34 Rabfakovskaya, Ivanovo, 153003, Russia

Abstract. Current research is devoted to the computer-aided engineering application for direct modeling of the additive manufacturing process and detailed analysis of the resulting shape of the formed part. The utilized approach is based on the idea that it is possible and efficient to perform a numerical simulation of the process of a layer-by-layer building of the analyzed part, considering all the required mechanical and thermal effects. The results of such simulation should allow obtaining the detailed information about the deformed shape of the printed part before running the printing process itself. Such approach allows avoiding the unsuccessful printing attempts, improve the integral stability of the production process and reduce its cost. The paper presents the methodology of preparing a “digital twin” of the additive manufacturing process performed with AlSi10Mg alloy using one of metal machines and running a simulation of the manufacturing process for a representative structural component. The study has shown that implementation of modeling of the manufacturing process before the printing process leads to significant shape improvements of the parts printed, especially in case of performing additional optimization of the support structures. The research outcomes can be well applied for improving the production processes in the companies working with additive manufacturing in order to increase the stability of the processes and accuracy of the printed parts.

1. Introduction
Additive methods as advanced manufacturing technologies allow producing the complex metal parts and assemblies, which have been previously unfeasible from the technological point of view [1]. However, regardless of all outstanding capabilities of metal additive manufacturing, this group of technologies has an important weak point, i.e. all metal additive manufacturing methods are characterized by the high possibility of deviations between the nominal shape of the part and its printed shape [2]. This specific feature causes additional limitations and introduces difficulties to the manufacturing process, which finally increase the cost of production and its duration.

Due to this fact, each of the companies, which produce or operate additive machines, generate their own knowledge base or “know-how”, which allows them to improve the stability of the manufacturing process and increase the printing accuracy. Such bases, as well as the knowledge of the technological staff, are highly valued by the companies.
Current research is devoted to the application of computer-aided engineering for direct modeling of the additive manufacturing process and detailed analysis of the resulting shape of the formed part to increase the stability of the processes and accuracy of the printed parts.

2. Review of current researches

Most of the works devoted to modeling of the additive processes date back to 2012 and later years. There are some studies, which were done and published earlier, but the amount of such publications is much lower. It may be assumed that this is caused by the increase of the availability of the additive machines, but there is another important reason – the increase of the performance of the computers, which are required for solving the complex thermomechanical tasks related to the printing process.

One of the most detailed and recent works on the subject of modeling the additive processes is [3], which was published by the group of researchers led by Pan Michaleris, the founder of the pioneering company in the field of direct modeling of additive manufacturing, acquired by Autodesk. This book describes and discusses most of the issues related to the modeling of thermomechanical effects that arise, when modeling the process of selective laser melting with metal powders.

In their earliest studies [4-7] the group assessed the efficiency of the approach of modeling the additive manufacturing using the technique of “birth” and “death” of finite elements and studied how the surface thermal interaction affects the results of the simulations. It should be mentioned that at the moment the technique of “birth” and “death” is an industry standard of modeling the additive process of adding the new layers for the finite-element systems designed for performing the additive simulations.

But there is a significant difference between the physical layers, which are used during the printing, and the virtual layers that are used to simulate the additive manufacturing. The reason for the difference is that the layers in the simulations are the macro-layers with the thicknesses, which are much higher than the thickness of the real layers. The implementation of the macro-layers is discussed in [8, 9]. The researchers conclude that this approach is fully applicable and correct, but it is mentioned in the study that there are many difficulties with the simulation process related to the high computational cost of the thermomechanical problems.

However, despite the fact that the metal additive manufacturing is a relatively new technology, the basic principle of the technology, which is based on the application of layers of melted material, is well known for a long time. It is widely used in welding, and the technology of finite-element modeling of the welding process was discussed in [10] based on the results of a study carried out in 1975.

In addition to the numerical approaches, some groups of researchers make attempts of performing the simulations of the build process using hybrid approaches, which are partially based on some analytical and pseudo-analytical methods [11, 12]. According to the study, the use of hybrid method can significantly accelerate the modeling process. Such acceleration could be extremely useful, since the existing approaches, which are based on numerical methods only, require a lot of time to perform the build simulations with high accuracy.

Along with the studies of the problems related to the modeling of the additive process itself, several groups of scientists focus their work on the studies of the procedure of generation of the optimal support structures [13, 14]. Such structures are required both for geometrical supporting the printed part and making it possible to print them and for the thermomechanical support that does not allow the parts to separate from the build plate and provides the conditions for the proper heat transfer. The developed approaches are based on such technologies as direct modeling of additive manufacturing and topology optimization.

The brief review of the current studies presented above makes possible to conclude that the area of application of computer-aided engineering to the modeling of the additive layer processes is still in the phase of intensive development, and the existing results and tools are very promising and allow improving the quality of the metal prints.

3. Simulation software

This article describes the process and the results of the simulation of additive manufacturing based on the finite-element modeling software called Amphyon, which is developed by Additive Works GmbH.
It is a relatively new tool, as well as all other systems working with this type of simulations. The user interface of the software is shown in Fig. 1.

![Graphical user interface of Amphyon by Additive Works.](image)

The study was performed with Amphyon 2019, which has the following modeling capabilities:

- optimization of the orientation of the part on the printer platform;
- generation of support structures;
- optimization of support structures in terms of structural integrity and thermal effects;
- simulation of the 3D printing process using rational finite-element mesh models;
- generation of deformed and predeformed shapes of the parts allowing to print the analyzed parts with the nominal geometry;
- modeling of thermal fields for the printed parts.

The first and the last points from the list above were not used in current study.

It is important to mention that Amphyon is based on a specialized finite-element solver, unlike many other similar software tools. This feature allows using specific algorithms, which are optimized for solving a narrow class of numerical problems with a high efficiency both on CPU’s and on GPU’s with good parallelization, which is very important due to the high computational cost of the considered type of tasks.

4. Analyzed object

The modeling in the study is performed for a representative complex part, which is a service bracket that is installed on a jet engine [15]. The shape and the size of the bracket are explained in Fig. 2.
Figure 2. The analyzed bracket.

The bracket has four points that are used to mount the part onto the engine and two padeyes, which are loaded with some forces and torque.

The study considers virtual printing of the bracket in two problem statements and describes the comparison of the real prints. In order to make the results comparable and more representative, the orientation of the bracket on the printing platform is not optimized.

5. Modeling of the 3d printing process

5.1. Approach of modeling

Due to the high complexity of the physical processes, which are to be described to simulate the additive layer manufacturing, the numerical models in most of the software tools are based on the following parameters of the material and printing process:

- elastic modulus;
- Poisson ratio;
- yield strength;
- layer thickness;
- results of measurements performed for a series of calibration specimens.

There is a significant point in the list above, which requires performing a number of measurements for 3D printed tests specimens. It may seem strange that some additional measurements shall be done, but there is an important reason for that. The reason is that the results of additive manufacturing strongly depend on the material properties, machine type and printing parameters. It means that in case of printing two parts made of the same material, with the same machine, but with different parameters of the printing process, the resulting parts will have identical chemical composition, but they may have different microstructure and behave differently from the mechanical point of view.

This specific feature shows that proper modeling of the 3D printing process requires the typical material data, but it also requires the printing parameters, which can be obtained in the simplified and integrated form as the results of measurement of the printed calibration specimens.

Of course, it may seem reasonable that the simulation could be run without the calibration of the numerical algorithm, but with some additional data about the material and the printing process instead. This concept is correct, but there is an important fact that taking into account the additional parameters of the material and process requires carrying out additional measurements and natural experiments, which require printing more specimens.
This allows making a conclusion that the approach based on using several calibration specimens should be quite efficient to provide accurate modeling results.

5.2. Calibration specimens

Each of the developers of the software that is designed for the additive simulations suggest a specific shape of the calibration specimen and a specific approach of the calibration, but the general idea is the same.

Additive Works recommend running the calibration based on the results of printing and measuring of three calibration specimens.

The main concept is that the specimens are printed and partially separated from the platform in such a way that they can deform as it is shown in Fig. 3. The deformation is affected by a number of parameters of the process of additive manufacturing, so it can provide a kind of integral indicator. The analyzed value of deflection is shown in Fig. 4.

![Figure 3. The calibration specimens in the neutral and deformed conditions.](image)

![Figure 4. The analyzed value of the deflection.](image)

Since the properties of the additive material depend on the history of the building process, it is recommended to consider the behavior of several calibration specimens, which are printed with different laser scanning strategies shown in Fig. 5.

![Figure 5. The scanning strategies: (a) balanced, (b) parallel and (c) perpendicular.](image)
The “balanced” strategies are usually the default strategies that are used for the printing tasks, because they allow getting the most stable, precise and isotropic results. The remaining “parallel” and “perpendicular” strategies are not balanced, because in these strategies one of the scanning directions dominates over another. The first specimen with the first scanning strategy shall have the highest level of deformation, and the specimen with the second strategy shall have the lowest deformation among all specimens. The unbalanced strategies usually lead to higher level of anisotropy and shape deviations in the printed parts.

5.3. Preparing the “digital twin” of the process

As it was mentioned, the process of calibration of the numerical algorithms of the software is started based on the input of the properties of the materials and based on the values of the deflection. During the calibration the system adjusts the parameters of the process in such a way that the resulting deflections of the virtually printed specimens equal the real experimental deflections. As the result, an object that might be called a “digital twin” of the process is generated. The term represents the set of characteristics and parameters, which allows the virtual printing of the parts.

The analyzed bracket is printed with AlSi10Mg aluminium alloy with the following mechanical properties:

- Young modulus – 76 GPa;
- Poisson ratio – 0.33;
- yield strength – 230 MPa.

The deflections of the calibration specimens equal:

- balanced strategy – 0.81 mm;
- parallel strategy – 1.08 mm;
- perpendicular strategy – 0.50 mm.

The layer thickness is 50 μm. The window of Amphyon showing the parameters of a “digital twin” is presented in Fig. 6.

![Figure 6. The window of Amphyon with the parameters of a “digital twin”.
](image)

6. Generation and optimization of support structures

The research considers the printing of the analyzed bracket with two types of support structures – regular and optimized. Both types of supports are prepared in Amphyon.

The regular support structures are generated in Amphyon based on the value of the critical angle of 45 degrees with the standard settings. The resulting shape of the regular perforated support structures is shown in Fig. 7.
The optimized support structures are generated based on the results of the finite-element modeling of the printing process. The simulation starts with the geometry of the regions, which shall be filled with the support structures, shown in Fig. 8. The curve showing the variation of the deformation and volume of the support material is presented in Fig. 9. A series of fields illustrating the changes in the density of the support structures during the optimization process is shown in Fig. 10.
7. Simulation of the additive manufacturing process

7.1. Finite-element meshing

The process of preparing the analysis model starts with the generation of the finite-element mesh on the main object and on the support structures. The characteristic size of the element in the build direction defines the thickness of the macro-layers. Amphyon is capable of generating the mesh of two types: regular and adaptive. The difference between the types is that in case of adaptive mesh the elements become larger closer to the center of the printed object. Such approach allows reducing the number of equations in the system without any significant effect on the results.

Current study is based on the adaptive finite element mesh with the characteristic size of 1 mm both in the plane of the build platform and in $Z$ direction. The generated mesh is presented in Fig. 11.
7.2. Simulation

The mesh generation is followed by the simulation itself. Before running the analysis it is required to set up several parameters, which define the type of the scanning strategy, which is used for printing the part, and the type of postprocessing or heat treatment that should be done.

In current research it is assumed that the additive manufacturing is done with the balanced scanning strategy, and that there is no heat treatment in order to maintain the integrity of the study of the effect of the part predeformation based on modeling.

After starting the simulation the system solves the task and shows the build process in the real time. The final results of the simulation are presented in Fig. 12. Several steps of the process are shown in Fig. 13.

7.3. Application of the results of the simulation

As it was discussed earlier in the document, the final goal of the additive simulation is to improve the geometry of the printed parts and stability of the printing process itself.

One of the possible types of result output from Amphyon are the deformed and predeformed shapes of the analyzed part. The deformed shape provides the information about the level of geometrical...
deviations of the printed object. The predeformed shape in case of printing allows getting the original part with the nominal geometry.

8. Results
In order to estimate if the simulation of the 3D printing process has any significant result on the accuracy of the printed part, several brackets were printed:
- bracket based on the nominal geometry;
- bracket based on the predeformed geometry, which was obtained with the regular support structures;
- bracket based on the predeformed geometry, which was obtained with the optimized support structures.

The comparison between the real printed shapes and the nominal geometry of the bracket is shown in Fig. 14-16. The fields are the result of 3D scanning performed for the printed parts.

**Figure 14.** The field of geometrical deviations between the nominal geometry of the bracket and the shape of the part that is printed based on the nominal geometry of the bracket, μm.

**Figure 15.** The field of geometrical deviations between the nominal geometry of the bracket and the shape of the part that is printed based on the predeformed geometry of the bracket with the standard supports, μm.
9. Conclusion
The results of the simulation of the aluminium bracket additive manufacturing process are presented in the paper.

The comparison of the deviation fields obtained for the 3D printed brackets allows making a conclusion that the shape of the bracket, manufactured based on the simulation, has significantly lower values of the shape deviation from the nominal one.

Besides, the shape obtained with use of the optimized support structures matches nominal one even better than the shape with the regular supports. Both these facts mean that the simulation of the additive processes makes it possible to improve the results of the printing.

From the practical point of view, the research confirms that including a 3D printing simulation as a step before manufacturing process should lead to a significant improvement of the quality of the prints, reduction of the production time and costs. This can be a crucial advantage in the fast-growing additive manufacturing market.

The outcomes of the research can be well applied for improving the production processes in the companies working with additive manufacturing in order to increase the stability of the processes and accuracy of the printed parts.

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