Process Design for the Wire Arc Additive Manufacturing of a Compressor Impeller

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Abstract. Additive manufacturing or 3D printing slowly and steadily replaces traditional subtractive manufacturing, where parts are manufactured by sequentially removing pieces of the workpiece material. In 3D printing, the material is added in layers, which enables producing parts of complex geometric shapes made from expensive metals with higher productivity and economic efficiency. In order to perform 3D printing on an industrial scale, it is necessary to combine robotics with 3D printing software. This article presents the results of the process design for 3D printing of a compressor impeller prototype. A detailed methodology of customization of the KUKA industrial robot for the 3D printing process is given. Once the impeller model was created in the CAD environment, it was cut into layers in the slicer program. Special software for offline programming of industrial robots was used to translate the program into the robot language and perform 3D printing using an experimental robotic complex. As a result, a prototype of a low-carbon steel compressor impeller was printed using a welding machine and steel wire. The developed technological process was successful and proved that an industrial robot combined with a welding machine can be used as an industrial 3D printer for printing real machine parts.

1. Introduction
The compressor impeller is a mechanism for creating torque rod (see figure 1). The principle of its operation is used in aircraft engines. Piston-type mechanisms have long been become obsolete, as jet engines are lighter, more efficient, and run on cheaper fuel. The fixed blading can be adjusted to different mechanisms.

The impeller provides maximum thrust with a minimum fan diameter, so the demand for such mechanisms is very high. Currently, high-speed bladed electric motors are widely used in aircraft modeling of the F4 category (the model copies a jet aircraft).

Impeller motors are also used for engines of jet skis, boats, and other water transport. The system gives higher thrust and extraordinary efficiency with maximum acceleration and performance.

With the special design of the impeller, it is possible to achieve minimal noise and get rid of the loss of power of the working turbine. The body of the impeller engine is smaller than that of the propeller, while the useful power remains the same. The impeller (mounted on the rotor) is a multi-blade screw in an annular channel. Air drawn into the impeller under high pressure has some weight, so there is a jet thrust as a result of the movement of air masses. The force moves the machine or moves the working medium [1, 2].

Impellers are used in a variety of ways. These are not only large industrial turbines' engines, cooling towers or compressors but also small mechanisms, such as aquarium filters, pumps, engines of dishwashers, water jets.

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Figure 1. Compressor impeller.

High-quality alloys of heat-resistant steel, stainless steel of AISI 316 and AISI 304 grades, as well as various aluminum alloys serve as materials for the manufacture of impellers.

The workpieces undergo a complex of machining work for removing burrs, notches, and other defects. Turning and milling machines are used for this purpose. After that, the blades undergo heat treatment such as tempering and normalization. A set of tests for strength and hardness then follows.

The traditional technological process of manufacturing impellers consists mainly of machining operations (see figure 2). As a result, during the manufacturing process, about 50% of the material of the initial workpiece is wasted on metal shavings. Therefore, this process is economically unprofitable, especially when impellers are supposed to be made of expensive alloys.

Figure 2. The traditional manufacturing process of an impeller.

3D printing, on the contrary, enables using up to 100% of the feedstock material, while only about 10% of the mass of the final workpiece is lost during finishing machining. Moreover, the use of 3D printing helps to significantly reduce the number of manufacturing operations of the impeller (see figure 3), which makes this process both cost-effective and high-performance [3].

Figure 3. The alternative manufacturing process of an impeller.
An industrial robot manipulator in conjunction with a welding machine is used as a 3D printer. 3D printing is performed using the wire arc additive manufacturing (WAAM) technology, where welding wire is used as a feedstock material that is melted using an electric arc. Once the printing process is complete, the part is also subjected to heat treatment to improve its mechanical properties.

The purpose of this project is to design a technological process for 3D printing of the compressor impeller. This article describes the process itself, starting from the CAD designing and ending with the final part. The result of the study is a printed prototype of the low-carbon low-alloy steel impeller.

2. Materials and methods

The welding wire Sv-08G2S with a diameter of 1.2 mm is used as a feedstock material. The wire was deposited on a Fe37-3FN structural carbon steel plate of 16 mm thickness.

The robotic complex installed at the Irkutsk National Research Technical University is used as an industrial 3D printer (see figure 4). The robotic complex consists of: an industrial robot KUKA KR 210 R2700 prime (KUKA robotics, Germany), a Lorch SpeedPulse S3 mobil welding machine and a CO2 protective gas cylinder.

The wire is deposited using a gas metal arc welding method (GMAW). This method is also known as a metal inert gas (MIG) welding or metal active gas (MAG) welding process. In this method of welding, an electric arc generates between the wire and the substrate metal, resulting in the wire to be melted [4]. To protect the molten metal from air contaminants, the welding grade CO2 shielding gas is used with a gas flow rate of 10 l/min.

To create a 3D model of the impeller, the Autodesk Fusion 360 CAD software was used. The Ultimaker Cura slicer was used for slicing the model into layers. Then, the RoboDK software was used to simulate the printing process and program the KUKA industrial robot.

Figure 4. WAAM robotic complex installed at the INRTU.
3. Results
In order to print the impeller, it is necessary to create a 3D model of it at first (see figure 5). The model was created on the basis of the compressor impeller presented in the reference [5]. The size and shape of the impeller have been slightly changed to facilitate the printing process.

![Figure 5. 3D model of the compressor impeller.](image)

Once the model is created, it needs to be saved in STL format, which is recognized by the slicer program. Then the model is loaded into the slicer for further slicing into layers. The impeller size has been scaled down by 60% to reduce the printing time. The resulting model has a diameter of 80mm and a height of 30mm. With these geometric dimensions, printing takes about 43 minutes. After changing the geometric dimensions, configuring the print parameters follows.

First of all, it is necessary to specify the diameter of the wire used. For printing the impeller, the steel wire SV-08G2S with a diameter of 1.2 mm is used. The further parameters to be specified are the thickness (height) and width of the layer. In preliminary studies not included in this article, the following values were obtained: the average layer thickness is 2 mm, and the width of the deposited bead is 10 mm. These values were obtained during the deposition of wall structures at a travel speed of 3 mm/sec. This speed proved to be the most optimal for 3D printing using steel wire.

The next step is to select an algorithm for the movement of the welding torch during the printing process. This parameter is the most important because it determines the quality of the future part. We can also choose where to start printing each new layer. This is necessary in order to avoid the formation of such a defect as a seam. Seam forms if printing each new layer starts at the same point. Also, the formation of this defect could be caused by a slight slowdown of torch speed before the new layer, which is caused by software restrictions. Therefore, it is necessary to choose the correct starting point for printing each layer, so that seam will be invisible, or can be easily removed by finishing machining.

Since each layer of the impeller has a closed contour, and the diameter of the circles decreases gradually with each layer, the spiral algorithm is most preferable for printing this part. In a spiral movement, only the outer contour of the wall will be printed. The height of the torch will gradually increase as the layer thickness increases. In this way, the spiral is created along the contour of the model. Movements of the torch from one layer to another are excluded since the torch will gradually increase the height along the way.

After selecting the torch movement algorithm, adjustments of the print speed follows. As mentioned earlier, it was found experimentally that the most optimal torch travel speed for steel wire deposition is 3 mm/sec.
Once all the necessary printing parameters are set, slicing follows. After slicing, the layered model can be seen (see figure 6). The print time is also calculated automatically. In this case, the prototype of the impeller will be printed for 43 minutes.

![Figure 6. 3D model of the impeller after slicing.](image)

The next step is to save the slicing model of the impeller in the g-code format. G-code is the formal name of the programming language for computer numerical control (CNC) machines. This language is also supported by most modern 3D printers. The program in the g-code format is necessary for creating the trajectory of the torch movement during the deposition of metal wire. The G-code file is then loaded into the software environment for simulating and programming industrial robots. At first, it is necessary to create a robotic cell in an environment that includes a workplace, an industrial robot, and a work tool.

Once the g-code file is generated, the simulation of the printing process continues in the software for the offline programming of industrial robots. To use industrial robots as 3 or 5-axis 3D printers, offline programming tools are required to translate 3D printer programs into robot programs. This software enables achieving the same results with industrial robots as with 3D printers. Based on the slicing model of the impeller, the robot's trajectory is created and the final printing program is generated (see figure 7). Then the printing program is converted to a program written in the robot language.

![Figure 7. Generated torch path.](image)
Then the simulation of the printing process can be started (see figure 8). All points that the robot can reach will be colored green, and unreachable points will be colored red. In order to make the points accessible to the robot, they must be rotated relative to the desired tool path. According to the loaded model, the program automatically generates the trajectory of the torch movement.

![Simulation of the printing process](image)

**Figure 8. Simulation of the printing process.**

To perform a 3D printing project, it is required to define the coordinate system and the working tool. The coordinate system of the impeller must be combined with the coordinate system of the print workspace in order for the coordinate system of the actual working environment to be correctly defined. In addition, approach and retract commands must be created for the robot's starting and ending movements. To minimize the movement of the robot joints and keep the orientation of the working tool as constant as possible, it is necessary to use a tool orientation algorithm that ensures minimal changes in the orientation of the tool during printing. Positioning the robot requires determining the center point of the robot tool using target points located in Cartesian space.

The software automatically optimizes the robot's trajectory, avoiding singularities, axis constraints, and collisions. Next, it is required to enter the coordinates of the working area of the robot and the working tool from the real working environment, after which the software will once again check whether this program can be executed. After completing all calculations and checks, simulation of the printing process can be followed and it can be seen how the 3D printing process will proceed.

Once the simulation is complete, it can be seen what the impeller will look like at the end of the printing process (see figure 9).

After the successful simulation of the virtual program, the final program written in the robot language is generated. The post-processor converts the simulation to the corresponding robotic program. The features of each particular robot are taken into account by the post-processor. By default, each robot has a standard post-processor defined by the programming software. All KUKA industrial robots use the KRL language. The post-processors have the complete versatility to create highly specialized robotic manufacturing programs. Post-processors can be easily modified for each specific task. Since the robot controller has restrictions on the file size or the number of lines of code, long programs cannot be transferred to the robot. In particular, 3D printing programs can contain hundreds of thousands of lines of code. To overcome this obstacle, long programs need to be split into subprograms that will run sequentially after the main program is started.
Figure 9. Impeller after the printing simulation.

Once the program has been generated, it can either be sent to the robot directly from the simulator interface or transferred to a flash drive and loaded into the robot control cabinet. The program can be transferred directly from the computer to the robot using the file transfer protocol or other special protocols. To start transferring, the robot's IP address needs to be determined and the file transfer protocol settings need to be configured in the robot connection menu.

After loading the program on the robot, it must be checked on the teach pendant to detect programming errors. Commands can also be added or deleted on the teach pendant. If the program has been checked successfully and the torch trajectory is correct, the welding machine can be switching on to set welding parameters. Then the printing process itself can be started. The printed prototype of a steel impeller is shown at figure 10.

Figure 10. Printed impeller prototype.
The impeller has the following dimensions: diameter is 80 mm, height is 30 mm, the number of layers is 15, and the thickness of one layer is 2 mm.

4. Discussion

3D printing software in conjunction with software for offline programming of industrial robots helped to create and successfully print a steel prototype of a compressor impeller. However, in order to 3D print such parts at the industrial level, it is necessary to improve the robotic complex by equipping it with additional sensors and software tools of narrow specialization. For example, it is preferable to implement a technical vision system to remotely monitor the printing process. This is primarily required in order to control the printing process in real-time to prevent the formation of possible defects and deviations from the geometric dimensions of the part specified during the CAD modelling. In addition, the welding current, voltage, and wire feed rate must be monitored and measured during the printing process. To do this, welding machines must have feedback to be capable of in situ adjusting the welding parameters.

It also requires developing highly specialized software specifically designed for 3D printing using WAAM technology. Standard 3D printing software does not take into account all the peculiarities of complex metallurgical and welding processes, which are of great importance for 3D printing of metal products. The thermal welding cycle impact and changes in the microstructure directly affect the quality and mechanical properties of the deposited parts.

During this project, a scaled-down steel prototype of the compressor impeller was printed. This was done solely in order to reduce the printing time and prove the possibility of using a robotic complex in conjunction with 3D printing software to perform 3D printing utilizing the new WAAM technology. This technological process has been successful in terms of the optimization and implementation of the printing process. However, the quality of the deposited part can only be judged visually, since no tests of mechanical properties have yet been conducted. The results of the study of the steel microstructure of the deposited impeller, as well as the results of tests, will be presented in future publications.

The objectives of future research are to develop a technological process for printing parts made of expensive metals, such as titanium and nickel alloys. Steel can still be used for printing prototypes of parts, but the manufacturing of real functional parts requires a transition to new materials [6–20]. It is also necessary to develop a process for printing objects of more complex geometric shapes with larger dimensions.

5. Conclusion

Additive manufacturing is a promising area of research, as it enables producing parts of complex geometric shapes with significant savings in the amount of additive material used. Robotics, in turn, opens new opportunities for 3D printing at the industrial level. Robots can be used as industrial 3D printers, and the flexibility and adaptability of their programming capabilities correspond to the trends and demands of small, medium and large-scale manufacturing.

This article describes the process design for 3D printing of a compressor impeller steel prototype. The method of programming an industrial robot from creating a CAD model to printing a real part is described in detail. Since there is currently no specialized software for the wire arc additive manufacturing, the only solution is to optimize the existing software for 3D printers. The slicer enables cutting the CAD model into layers and setting printing parameters. Software for offline programming of industrial robots gives an opportunity to use industrial robots as 3D printers. The g-code generated in the slicer is easily recognized in the software and then translated into the robot's language.

The available software settings help to create programs for 3D printing both simple hollow shapes, such as a cylinder and square and quite complex objects, such as a compressor impeller. The technological process developed for printing the impeller was successful and proved that the robotic complex in conjunction with 3D printing software can be used for 3D printing of metal parts using WAAM technology.

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