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3D printing technology for metal products: from an automatic design system to a real part

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Abstract: The aim of the present study involves the adaptation of a robotic complex based on an industrial robot for 3D printing of metal products by arc welding, the development of a technological process system for printing a real part, as well as an evaluation of the potential for obtaining high-quality metal products using existing equipment. For 3D printing of metal products, a robotic complex based on a KR 210 R2700 PRIME industrial robot (KUKA, Germany) and an S3 mobil SpeedPulse welding machine (Lorch, Germany) were used. 3D object models for printing were created in Autodesk Fusion 360 software. The dedicated Ultimaker Cura 3D printing program was applied for slicing the models into layers. The simulation of the printing process and programming of an industrial robot was carried out using the RoboDK software (Canada). As a result, a technological process for 3D printing an impeller prototype from the design stage to the manufacture of a finished metal product has been developed. A detailed methodology for adapting an industrial KUKA robot for the process of metal product 3D printing using the arc welding method is presented. Following the creation of the 3D model of the impeller in the CAD system, its slicing into layers was performed in a slicer program. In the course of preliminary experiments, the optimal technological parameters of the torch movement speed during weld surfacing of 3 mm/s were determined for the 3D printing of carbon steel workpieces. A carbon steel impeller prototype was printed using a welding machine and a welding wire. The developed technological process for 3D printing of metal products using the arc welding method has demonstrated the potential use of an industrial robot in combination with a welding machine for use as an industrial 3D printer. Future studies will focus on developing a technological process for finishing parts produced by means of 3D printing, as well as printing parts from expensive materials and alloys containing titanium and nickel.

Keywords: additive technologies, industrial robots, 3D printing, gas metal arc welding, off-line programming

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Технология 3D-печати изделий из металла: от системы автоматизированного проектирования до реальной детали

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Резюме: Цель – адаптация робототехнического комплекса на базе промышленного робота для 3D-печати изделий из металла методом дуговой сварки, разработка системы технологического процесса для печати реальной детали и определение потенциала имеющегося оборудования для получения качественных изделий из металла. Для 3D-печати изделий из металла использовался робототехнический комплекс на базе промышленного робота KUKA KR 210 R2700 prime (Германия) и сварочного аппарата Lorch SpeePulse S3 mobil (Германия). 3D-модели объектов для печати создавались в программном обеспечении Autodesk Fusion 360. Для разделения моделей на слои применялась специальная программа для 3D-печати Ultimaker Cura. Симуляция процесса печати и программирование промышленного робота выполнялось при помощи программного обеспечения RoboDK (Канада). Разработан технологический процесс 3D-печати прототипа импеллера от этапа проектирования до изготовления готового изделия из металла. Приведена подробная методика адаптации промышленного робота KUKA для процесса 3D-печати металлических изделий с использованием метода дуговой сварки. После того, как 3D-модель импеллера была создана в системе автоматизированного проектирования, она была разрезана на слои в программе-слайсере. В ходе предварительных экспериментов были определены оптимальные технологические параметры скорости движения горелки при наплавке 3 мм/с для 3D-печати заготовок из углеродистой стали. При помощи сварочного аппарата и сварочной проволоки был напечатан прототип импеллера из углеродистой стали. Разработанный технологический процесс для 3D-печати изделий из металла методом дуговой сварки доказал, что промышленный робот совместно со сварочным аппаратом может быть использован в качестве промышленного 3D-принтера. В дальнейшем планируется разработка технологического процесса финишной обработки деталей после 3D-печати, а также печать деталей из дорогостоящих материалов и сплавов, содержащих титан и никель.

Ключевые слова: аддитивные технологии, промышленные роботы, 3D-печать, дуговая сварка в среде защитного газа, автономное программирование

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1. INTRODUCTION

Increased contemporary interest in additive technologies (AT) – so-called "3D-printing – in the industrial sector is primarily due to the need to develop cost-effective modern production technologies. ATs are applied for manufacturing parts having complex geometrical shapes with both high productivity and efficient utilisation of materials [1–5]. Of the many emerging AT approaches, one of the most promising is Wire Arc Additive Manufacturing (WAAM), which applies industrial robots in conjunction with welding equipment [6–10]. Due to its use of standard welding consumables, WAAM technology can be applied for printing parts from almost any metal alloy, including those manufactured from expensive titanium- and nickel-based alloys. As compared to traditional methods of manufacturing parts (machining), WAAM has a higher productivity (by 40–60%), resulting in a reduced finishing cycle by 15–20% depending on the dimensions of the product [11–15].

Here, the heat source is represented by an electric arc generated between the basic and the filler material. In terms of filler material, welding wires are used, being much cheaper than metal powders applied in other additive technologies. Along with the printing of new parts, WAAM can also be used for repair and refurbishment operations [16–20].

The traditional manufacturing process of impellers consists mainly in of machining operations of various types. For this, turning and milling complexes, as well as milling machines, are used. As a result, in the manufacturing process, more than 50% of the cost of the main blank part material is spent producing waste material in the form of metallic swarf. For this reason, such machining approaches are seen as economically disadvantageous, especially when the impellers are made of expensive alloys.

Conversely, taking the 3D printing approach ensures up to 100% of the useful weight of the filler material to be applied, while only about 10%wt. of the final blank part is lost during finishing machining. Thus, the application of 3D printing can significantly reduce the number of technological steps in impeller manufacturing, making this process both cost-effective and operationally efficient.

The aim of the present project is to develop a technological process for the 3D printing of impeller parts.

2. MATERIALS AND METHODS

Sv-08G2S welding wire, having a diameter of 1.2 mm, was used as a filler material. Wire weld surfacing was carried out on a steel plate 16 mm thick.

In terms of an industrial 3D printer, a robotic complex installed at the Irkutsk National Research Technical University was used (see fig. 1). The robotic complex includes: 1 – KUKA KR 210 R2700 prime industrial robot; 2 – Lorch SpeedPulse S3 mobil welding machine; 3 – CO_2 bottled shielding gas.

Wire weld surfacing was carried out by the gas metal arc welding (GMAW) method. This method is also known as metal inert gas or metal active gas. GMAW involves the generation of an electric arc between the filler wire and the metal of the blank part, resulting in the melting of the wire. To protect the molten metal from contamination, CO_2 shielding gas is used at a feed rate of 10 l/min.

In order to create 3D models of objects for printing, the software package of the computer-aided design (CAD) Autodesk Fusion 360 was used. The Ultimaker Cura slicer software was additionally applied to slice the model into layers and set print parameters. Next, the RoboDK software was used to simulate the printing process and program the KUKA industrial robot.

Following simulation and creation of the final print program, it is downloaded to the robot controller and then launched from the robot control panel.

3. RESULTS

In order to create the 3D model of the impeller part prior to printing, Autodesk Fusion 360 software was used (fig. 2). In order to facilitate the printing process, the dimensions and shape of the impeller have been slightly changed.

After the model is created, it must be saved in STL (stereolithography) format for recognition by the slicer software. Further, the model is loaded into a slicer software for additional slicing. Since, the requirement was to print a prototype impeller, the part was scaled down by 60% in order to reduce printing time.

After changing the geometric dimensions, the printing parameters are set resulting in a model 80 mm in diameter and 30 mm in height, for which geometric dimensions, printing takes about 43 minutes.

Prior to printing a number of steps must be carried out. First, the welding wire is specified as Sv-08G2S steel wire having a diameter of 1.2 mm. The next parameters to be specified are the thickness (height) and width of the layer. In preliminary studies not included in this article, average layer thickness and welding bead the width were obtained equal to 2 and 10 mm, respectively. These values were obtained during the weld surfacing of walls at a speed of 3 mm/s. This speed turned out to be the optimal for 3D printing with steel wire.

Fig. 1. Robotic complex for 3D printing: 1 – KUKA KR 210 R2700 prime industrial robot; 2 – Lorch SpeedPulse S3 mobil welding machine; 3 – CO_2 bottled shielding gas

Рис. 1. Робототехнический комплекс для 3D печати: 1 – промышленный робот KUKA KR 210 R2700 prime; 2 – сварочный аппарат Lorch SpeedPulse S3 mobil; 3 – баллон с защитным газом CO_2

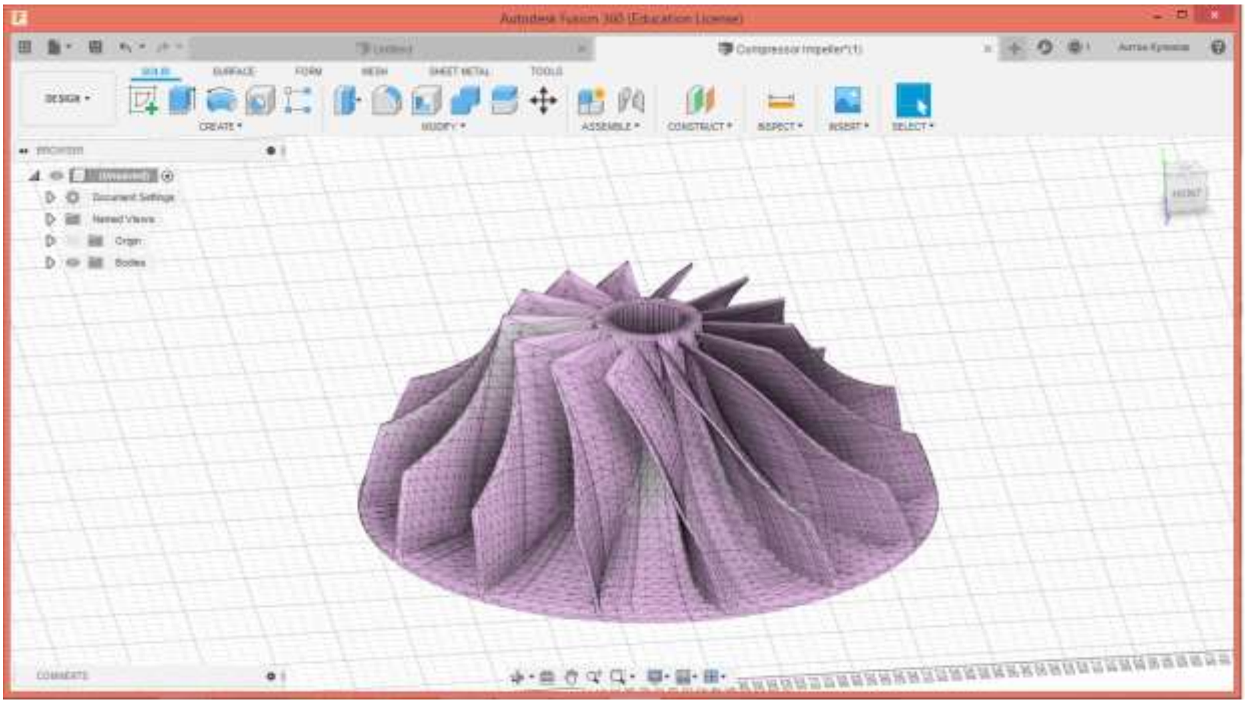

Fig. 2. Impeller 3D model
Рис. 2. 3D-модель импеллера

The next step consists of selecting the algorithm for the movement of the welding torch during the printing process. Due to its key role in determining the quality of the future part, this parameter is of particular importance. On this basis, the starting printing point of each new layer can be selected. This parameter is necessary for excluding such defect as overlaps, which occur when the printing each subsequent layer is started at the same point. The formation of such defects may also occur due to a slight slowdown in the movement of the torch prior to beginning the next layer as a consequence of software limitations.

Therefore, it is necessary to select the correct starting point for printing each layer so that the overlap is invisible or can be easily removed by finishing machining.

The torch movement can be optimised in the following ways:

1. Manual specification of the starting point for printing each new layer. With this method, the software algorithm places the point as close as possible to its specified coordinate. However, since, in this mode, each layer is printed at the same point, the overlap is formed at the start/end of the printing, thus leading to distortion of the part geometry, i.e. an uneven height of the outer walls and a widening of the wall in this location.

2. Printing starts at the closest trajectory point. This mode minimises the length of movements between layers. The printing start point can be located in different places. As the movements of the torch between layers become shorter, the duration of the entire printing process is significantly reduced. Additionally, the overlap is slightly less because less material will be surfaced where the torch starts printing a new layer. However, the point is still located as close as possible to the place where the torch is located at the moment of finishing the printing of the previous layer. Here, the average value is selected instead of the closest point coordinate value. This ensures a slight reduction in the movements and, at the same time, obtaining a suitable coordinate.

3. The new layer is printed in a random place. The printing start point changes with each layer for achieving an almost uniform wall surface. Since the printing start points of different layers do not match, the overlap is barely noticeable. The main advantage of this mode is that it results in the future part having a flat surface with accurate dimensions along all axes. Due to this algorithm, movements leading to the

appearance of potential defects are minimised.

4. Spiral movement algorithm. This mode supports the printing of objects, each of whose layers consists of one outline, along a spiral trajectory. As the torch rises gradually during printing, it is effectively impossible to distinguish the transition to each subsequent layer. This method provides for the complete elimination of overlap or any other defects occurring when the torch stops at the time of transition to each subsequent layer.

Since each layer of the impeller has a closed boundary and the diameter of the circles decreases gradually with each layer, the spiral torch movement algorithm is preferable for printing this part. With the spiral movement, only the outer contour of the wall is printed. The torch height will gradually increase as the layer thickness increases. Thus, the spiral is created along the contour of the model. In this case, the movement of the torch from one layer to the next is avoided since the torch gradually rises during printing.

After selecting the torch movement algorithm, the printing speed must be tuned. As mentioned earlier, the optimal speed of the torch in weld surfacing the steel wire was experimentally determined to be 3 mm/s. Although it is possible to be set the torch speed between layers, this setting is only recommended for objects incapable of being printed by the spiral method. The torch movement speed is usually much faster than the printing speed itself. A higher movement speed may shorten printing time slightly. However, an increase in the speed may quite likely lead to increased torch vibration due to the oscillation of the robot joints during sudden stops.

In order to fine-tune the printing process, it is recommended that the printing of additional test layers be added prior to printing the part itself. This is aimed at preparing the wire for weld surfacing the main part. The test layer is printed around the future part, followed by the torch movement along the programmed trajectory to the point where the main part is to be printed. No noticeable effect is caused by the test layer on the quality of the future part. Once all the necessary printing parameters are set, the part is sliced into layers. Following slicing, the layered model is as depicted in fig. 3.

The printing duration is also calculated automatically. In this case, the impeller prototype takes 43 minutes to be printed.

The following step implies saving the sliced impeller model in g-code format. G-code is the formal name of a programming language for numerically controlled machine tools. This language is supported by most contemporary 3D printers. A g-code software is required for creat-

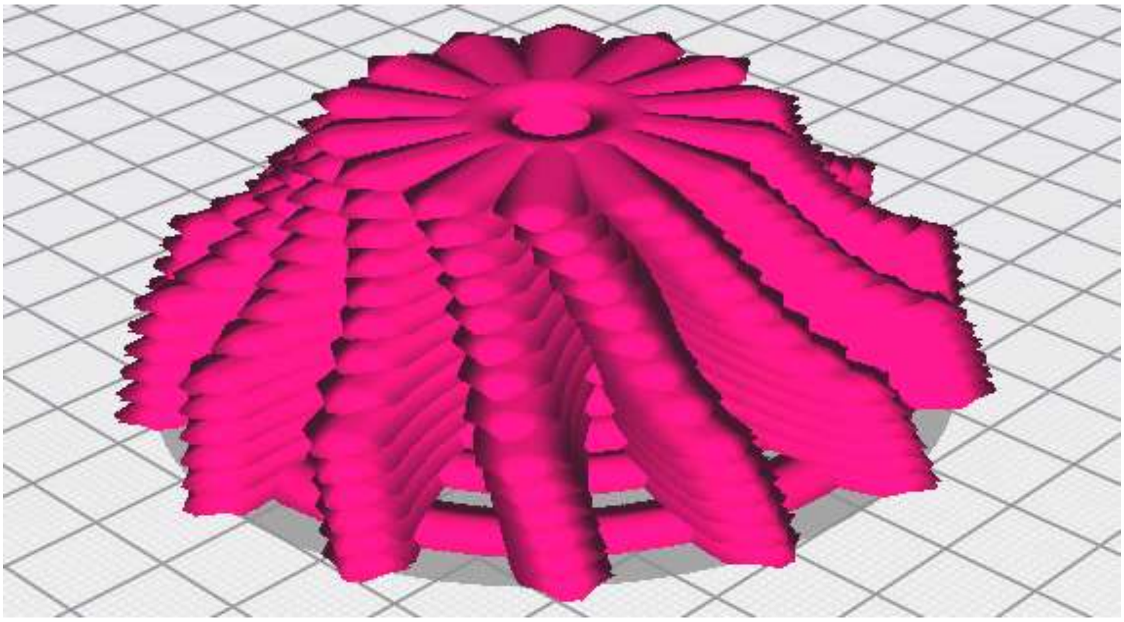

Fig. 3. 3D model of the impeller after layering
Рис. 3. 3D-модель импеллера после расслоения

ing a torch trajectory during metal wire weld surfacing. Next the g-code file is loaded into a software for modelling and programming industrial robots. It is necessary to create a robotic cell in the software (fig. 4) including: 1 – workplace, 2 – industrial robot, 3 – linear guide, 4 – working tool. The KUKA KR 210 r2700 prime robot is used for the impeller printing.

Following the creation of the g-code file, the modelling of the printing process continues in the off-line programming software for industrial robots. The off-line programming provides for testing and simulation of robotic programs in a computer environment to eliminate errors and malfunctions arising when programming by means of the robot control panel. Simulation and off-line programming ensure the analysis of several scenarios for a robotic cell prior to creating a robotic complex in a real industrial environment.

The off-line programming approach turns out to be the best way for optimising a robotic complex and ensuring the maximum efficiency of the robot application. Due to the off-line programming, new technologies such as WAAM can be tested and optimised as soon as possible, thus accelerating the process of introducing robotic 3D printing into real production scenarios.

An application of industrial robots in terms of 3- or 5-axis 3D printers requires off-line programming tools for translating 3D printer programs into robot operation programs. This software ensures the achievement of the same results with industrial robots as with 3D printers. Based on the layered impeller model, the robot's trajectory and the final printing program are created. The printing program is then converted into a program written in the robot software language.

In order to carry out a 3D printing project, it is necessary to define a coordinate system and a working tool. The impeller coordinate system must be aligned with the work area coordinate system for the correct definition of the actual printing work environment. In addition, approach and return commands must be created for the starting and ending movements of the robot.

In order to minimise the movement of the robot joints and keep the tool orientation as constant as possible, a tool orientation algorithm should be used that minimises tool reori-

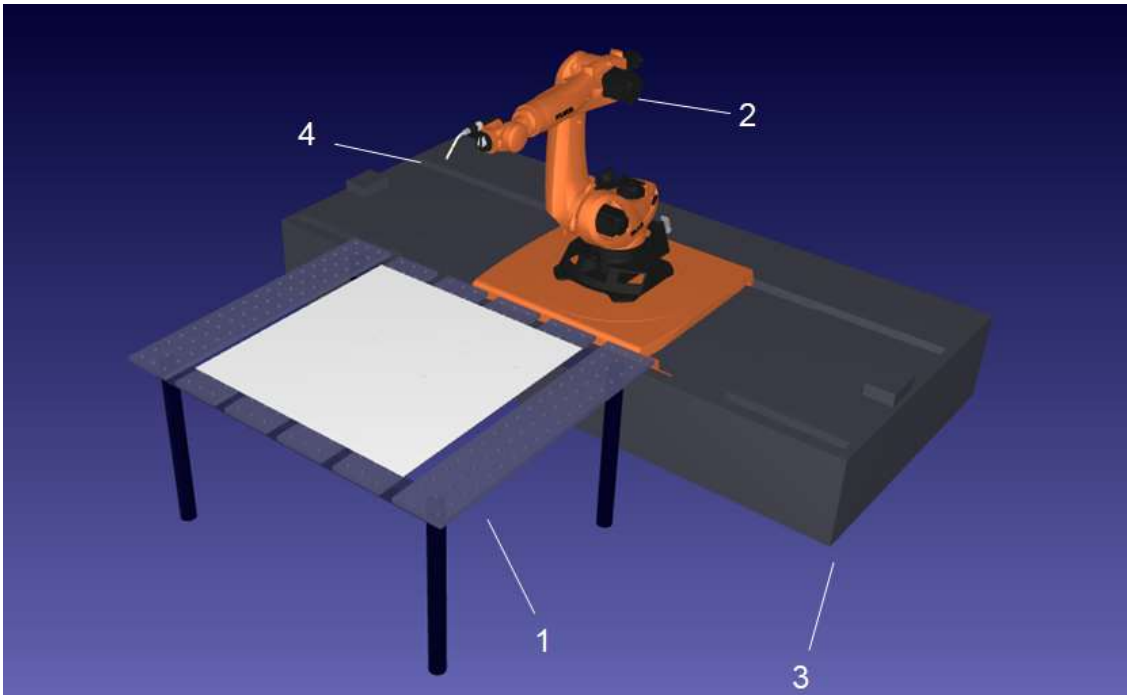

Fig. 4. Robotic cell: 1 – workplace; 2 – industrial robot; 3 – linear guide; 4 – working tool
Рис. 4. Роботизированная ячейка: 1 – рабочее место; 2 – промышленный робот; 3 – линейная направляющая; 4 – рабочий инструмент

entation during printing. Positioning of the robot requires the centre point of the robot tool to be defined using target points located in Cartesian space. In order to ensure more accurate results and avoid tuning errors, the centre point of the robot tool must be correctly defined using more than 3 or 4 tool position configurations. Typically, 8 or more points are required for the most accurate tuning. However, in cases where only moderate precision required, 3 points appear to be sufficient.

The printing object's location relative to the robot is determined by defining an external coordinate system. For this, it is necessary to touch several points using the working tool. Before defining the external coordinate system, the centre point of the robot tool must be properly calibrated. However, points measured with an external measuring system can also be used.

Having carried out the previously described steps, the printing process simulation can be started. All points reachable by the robot will be coloured green, as opposed to the unreachable points coloured red. In order to make the red points reachable by the robot, they must be rotated relative to the desired tool trajectory. If some points cannot be reached, either the coordinate system must be moved or the number of restrictions on the tool rotation reduced.

Additionally, in order for all the specified settings to take effect, the program should be updated. If the program has been successfully saved, a green check mark appears in the settings field.

A new printing program will then appear on the station with the calculated tool trajectory coloured in green.

The part should be located in a convenient place for printing, where the robot can easily execute the downloaded program. In accordance with the loaded model, the program automatically generates the trajectory of the torch movement (fig. 5).

The downloaded g-code file is checked for errors and the capability of the robot to execute this program. The software provides for the additional functions to be included in the printing process, such as turning on and off the electric arc, as well as additionally setting the speed of movement, approach and return of the robot. However, the welding torch must be properly calibrated so that its centre point exactly matches the point from which printing begins.

The software automatically optimises the trajectory of the robot, avoiding singularities, axis constraints and collisions. Next, the coordinates of the robot working area location and the working tool from the real working environment are to

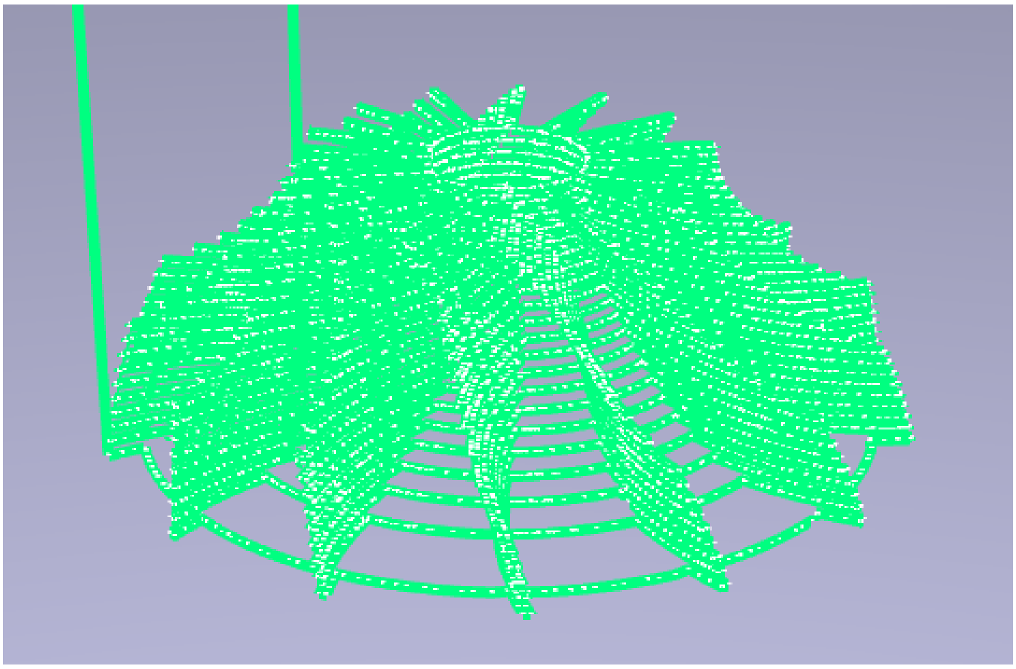

Fig. 5. Torch movement trajectory
Рис. 5. Траектория движения горелки

be entered, followed by another check in the software to confirm the possibility of executing the program. After completing all calculations and checks, the printing process can be simulat.

After the simulation is complete, it is possible to observe the visual appearance of the impeller following the printing process (fig. 7). After successful simulation of the virtual program, the final program is written in the robot language. The postprocessor converts the simulation to the corresponding robotic program. In this case, the features of each specific robot are taken into account by the postprocessor. By default, each robot has a standard postprocessor defined by the off-line programming software. All KUKA industrial robots use the KRL language.

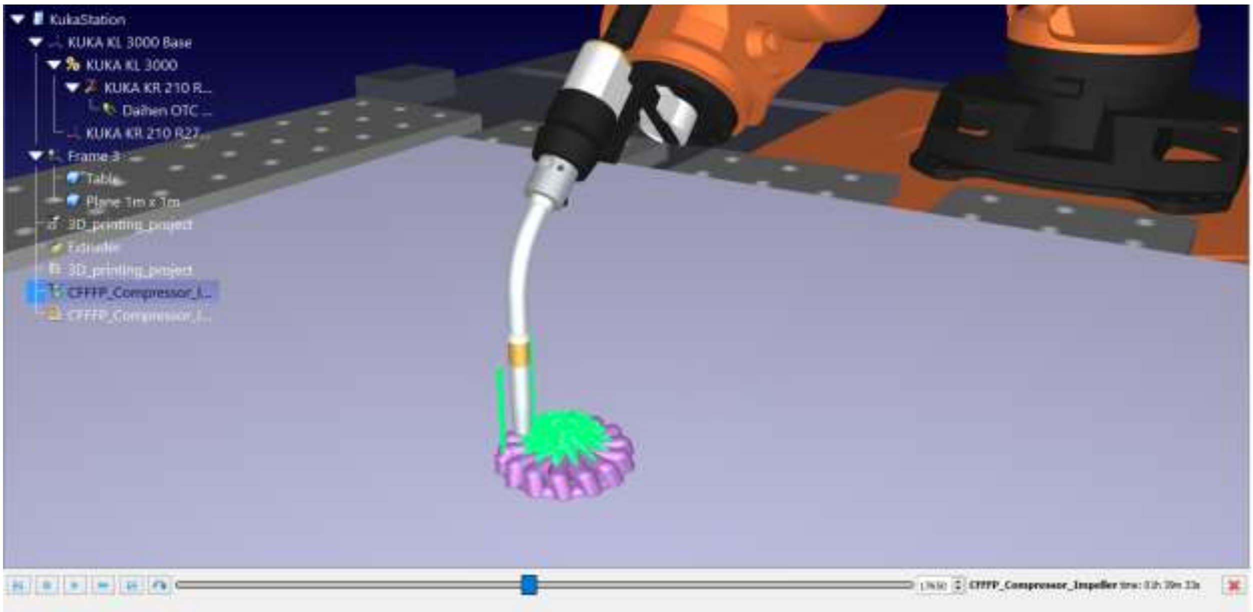

Fig. 6. Printing process simulation
Рис. 6. Симуляция процесса печати

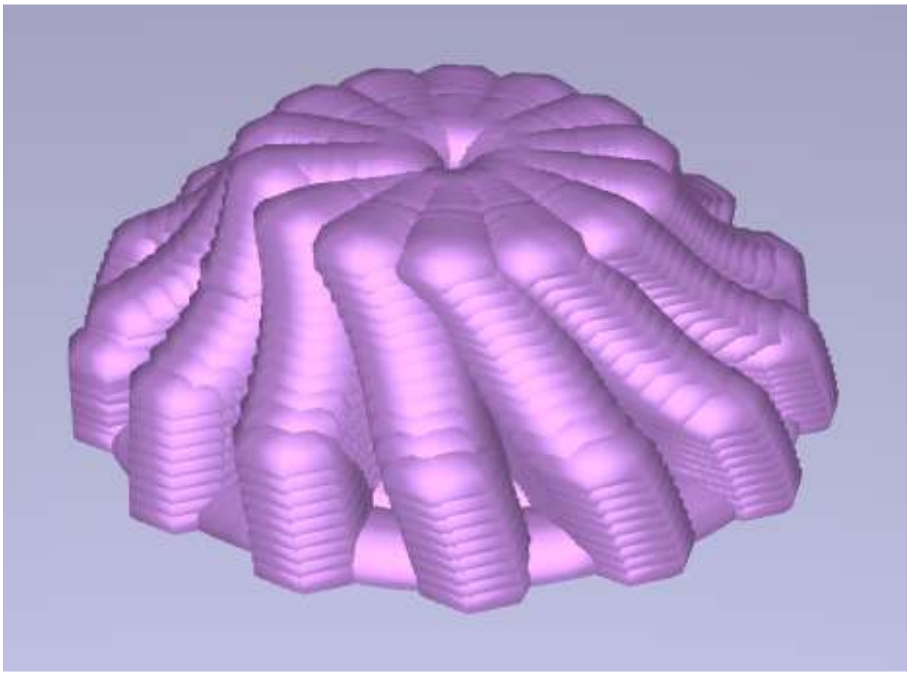

Fig. 7. An impeller after printing simulation
Рис. 7. Импеллер после симуляции печати

Postprocessors have full versatility for creating highly specialised robotic programs and can be easily modified for each specific task. Since the robot controller has limitations on 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 code lines. In order to solve this problem, it is necessary to break long programs into subprograms executed sequentially after the main program starts.

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's control cabinet. The program can be transferred directly from the computer to the robot using file transfer protocol (FTP) or other special protocols. For starting the transfer, it is necessary to determine the IP address of the robot; the file transfer protocol parameters are to be configured in the robot connection menu.

After downloading the program to the robot, it must be checked on the control panel for the programming error identification. The remote control also has the ability to add or remove missing commands. In the case of the program being checked successfully and the correct torch trajectory established, the welding machine can be turned on with the setting of the welding modes. Then, the printing process itself can be started.

A printed prototype of a steel impeller is shown in fig. 8.

After weld surfacing of the impeller, finishing machining will be carried out at the milling processing complex. This processing consists in the removal of the allowance, which is specified at the stage of product design.

4. DISCUSSION

The 3D printing software combined with the off-line programming software for industrial robots has enabled the development and successful printing of a steel impeller prototype. However, in order to carry out 3D printing of such parts at an industrial level, it is necessary to improve the robotic complex by equipping it with additional sensors and narrowly specialised software. For example, it is necessary to implement a vision system for remote monitoring the printing process. This is required primarily in order to ensure the control of the printing process in real

Fig. 8. Printed impeller prototype
Рис. 8. Напечатанный прототип импеллера

time and prevent the appearance of possible defects and deviations of the geometric dimensions of the part from those specified in the CAD design. In addition, the welding current, voltage and wire feed rate must be monitored and measured during the printing process. For this, welding machines must have feedback capabilities in order to be adjust the welding modes during the printing process.

Thus, there is a requirement for highly specialised software specifically designed for 3D printing using WAAM technology. Despite their great importance for 3D printing of metal products, no accounting of the special features of the complex metallurgical and welding process is performed by the standard 3D printing software. The thermal cycle of welding and changes in the microstructure directly affect the quality and mechanical properties of the welded parts.

In the course of this project, a small-scaled prototype of the impeller was printed. This was done solely in order to shorten the printing time and prove the possibility of using a robotic complex in conjunction with the software for 3D printing using the new WAAM technology. This technological process has been shown to be successful in terms of optimisation of printing performance. However, the quality of the weld surfaced part can only be judged visually, since no tests of mechanical properties have yet been carried out. The results of the microstructure study of the metal of the weld-surfaced impeller, as well as the test results, will be presented in future publications.

Future research is aimed at the development of a technological process for printing parts from more expensive metals such as titanium and nickel alloys. Although steel can still be used for printing part prototypes, the production of real parts requires a transition to new materials focusing on the development of a process for printing objects of more complex geometric shapes and having larger dimensions.

5. CONCLUSION

Additive manufacturing represents a promising area of research, due to the possibility of producing parts of complex geometric shapes to significantly save the amount of used filler material. Robotics, in turn, opens up new possibilities for industrial 3D printing. Robots can be used as industrial 3D printers with the flexibility and adaptability of their programming meeting the trends and characteristics of small-, medium- and large-scale production.

This article describes the technological process for 3D printing of an impeller prototype. The method of programming an industrial robot is described in detail, from creating a CAD model to printing a real part.

Since there is currently no specialised software for 3D printing of metal products, one possible approach consists in optimising the existing software for 3D printers.

The slicer software provides the slicing the CAD model into layers and setting the print parameters. Off-line programming software for industrial robots ensures their application as 3D printers. The g-code generated in the slicer software is easily recognised in the program and then translated into the robot's language.

According to the available software settings, the creation of 3D printing programs is possible both for simple hollow shapes, such as a cylinder or square, as well as for fairly complex objects such as impellers. The technological process developed for the impeller printing was demonstrated to be successful, confirming the applicability of the robotic complex + 3D printing software combination in 3D printing of metal products using WAAM technology.

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Authorship criteria

Kulikov A.A. performed 3D modeling, developed the technological process of wire arc manufacturing and wrote the article. Nebyshinets Yu.V. was responsible for the adjustment of the welding machine and selection of welding modes. Sidorova A.V. helped with operating and programming of the KUKA industrial robot. Balanovskii A.E. supervised the overall project and participated in the discussion of the results obtained.

Критерии авторства

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Conflict of interests

The authors declare that there is no conflict of interests regarding the publication of this article.

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