A Practical Toolpath Planning Method for Cold Spray Additive Manufacturing of Rotational Symmetry Parts

Hongjian Wu *, Alexander List, Frank Gärtner, Thomas Klassen
Institute of Materials Technology
Helmut Schmidt University/
University of the Federal Armed Forces
Hamburg, Germany.
*wuh@hsu-hh.de

Marcel Lewke
Institute of Automation Technology
Helmut Schmidt University/
University of the Federal Armed Forces
Hamburg, Germany

Abstract – **Rotational symmetry parts are common and essential in industrial applications. Cold spray additive manufacturing (CSAM) is an attractive and rapidly developing solid-state material deposition process, providing an efficient and convenient method for producing such parts, as it allows for the rapid formation of high-quality, large-volume 3D objects. Since there is no highly reactive liquid phase involved in this process, the deposited material is free of oxides. As compared to conventional additive manufacturing methods, cold spraying enables to reduce the production costs and times.**

In this work, a general implementation method for CSAM of rotating symmetry casing parts is presented. Here, the developed application can handle rotational symmetry parts of arbitrary geometry in the form of CAD files to generate precise toolpaths. Robot offline programming allows for process simulation, analysis, and optimization. Additionally, modelling of robot kinematics is employed to evaluate the effect of the planned toolpaths on the spraying process, ensuring efficient and precise manufacturing processes.

Keywords* – *Cold spray, additive manufacturing, toolpath planning, rotational symmetry part

I. INTRODUCTION

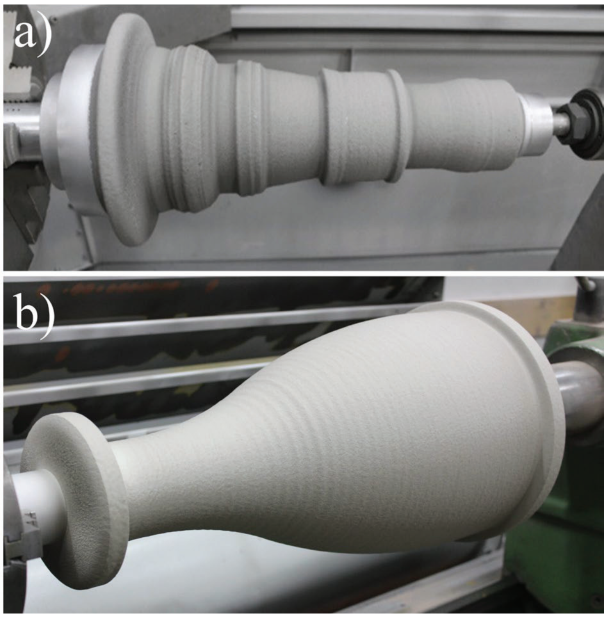
Cold gas dynamic spraying, or cold spraying (CS) for short, is a rapidly evolving solid powder deposition technique. In this process, micron-sized powders are accelerated to supersonic velocities by a high-pressure gas flow through a convergent-divergent de-Laval nozzle. The particles remain at a temperature below the melting point. The impact on the solid surface results in severe localized plastic deformation and a temperature rise, causing local interface softening and enabling the formation of deposits by adiabatic shear instabilities [1]. CS was initially used for developing various functional surface properties, ranging from protection against harsh environments to specifically tailored surfaces in electronic applications [2]. Nowadays, in industry and research laboratories, serious attention is paid to topics of CS-based additive manufacturing (AM) as well as to applications in repair or remanufacturing techniques [3], [4], [5]. Unlike the usually used thermal AM techniques involving melting, cold spray additive manufacturing (CSAM) solely involves solid state deposition. This implies that oxidation as pronounced by fast reaction kinetics in the molten state and the formation of undesired phases or substructures associated with rapid solidification can be avoided. In addition, CSAM can reach high spraying rates of up to 10 kg/h and allows for fabrication of complex and larger parts assisted by industrial robots. Therefore, CSAM is considered as an effective and economic solution for manufacturing of heat sensitive materials (especially pure titanium, copper, aluminium, and their alloys) and rapid fabrication of large-volume parts.

Casing parts with rotational symmetry are commonly used in engineering structures, such as casings of aircraft engines, gas turbines, pumps, and wind power plants. These components usually have features such as specialized flanges or bosses on the periphery. Conventional manufacturing methods are performed through a combination of several turning and milling processes, which are often very intricate and costly, resulting in significant material waste. CSAM enables to create the contour of the component close to the final shape easily by introducing an external rotation axis driven by an individual electrical regulator. Many similar cases have been reported [6], [7], e.g. a fan shaft [8] (as shown in Figure 1a) and a rocket nozzle [9] (as shown in Figure 1b) fabricated using CSAM. However, the implementation methods are not clearly explained in the reports.

The present work aims to develop a general implementation strategy and toolpath planning method for CSAM of rotating symmetry casing parts. In the practical spraying process achieving precise control over kinematic parameters is essential for successful shape buildup. This involves assigning the coordinates of each point on the part surface and specifying associated conditions, such as spray angle and local scanning speed. All that could be correlated to associated robot movements as well as obtained layer deposition and guide to more profound toolpath development.

II. GENERAL CONCEPTS

The general AM process involves two phases dealing with design and printing. These phases can be further divided into four steps: (i) digital modelling; (ii) pre-processing, involving simulation and preparation of the files for 3D printing; (iii) printing; (iv) post-processing, including removal of the support and separation of the parts. In order to introduce the basic idea of AM into the CS process, a generic CSAM implementation process is proposed based on existing generic technical configurations and layouts.



FIGURES 1: ADDITIVE MANUFACTURING (A) STAND-ALONE TURBOJET ENGINE FAN SHAFTS AND (B) ROCKET NOZZLES WITH COLD SPRAYING ACCORDING TO *[8] and [9]*

The first step of the process is to design an initial geometry and to create a CAD file of the printed object. After establishing the CAD model, the step of analysing the features of the object and formulating corresponding building strategies is completed by simulation tools, which mainly involve toolpath planning and generation as well as analyses and adjustments of robot motion programs. Currently, generic strategies for material buildup are proposed for rotational symmetry casings. The corresponding toolpaths are planned according to the axial cross-section of the part. A previously established numerical model to obtain 3D CS deposits [10] is applied to determine path parameters. A custom developed script is used to automatically generate the desired toolpaths. It takes CAD files as input and generates the toolpaths in the form of a 6-axis robotic arm program as output.

Before actually depositing material for building the part, it is essential to carefully check the generated robot trajectory program. This should ensure that no singularities arise in the robot joints, or a specific robot axis reaches its motion limits during the workpiece deposition process. If such situations occur, adjustments to the robot program or even re-planning of the toolpath are required. In addition, machine collisions must be avoided. Therefore, process simulation via a virtual workstation established in robot offline programming software is necessary to enable machine accessibility and collision detection. Additionally, it facilitates the analysis of robot kinematics, adjustment of toolpaths and buildup processes as well as the calculation of manufacturing time. After calibration and debugging of the manufacturing program in the actual spraying workshop, the spraying process can be implemented to build the initial shape. The details of the part and the needed tolerances require further machining (e.g. drilling, edge chamfering, and final dimensional finishing).

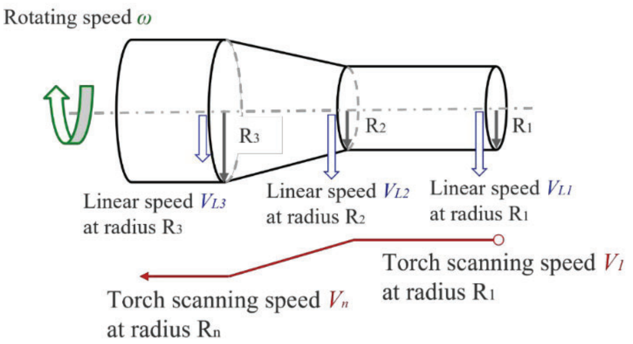
III. BUILTUP STRATEGIES FOR ROTATIONAL SYMMETRY PARTS

A. Path Parameter Determination: Scanning Speed

CSAM is capable of producing various rotational structures including free-form cylinders and cones. In the depositing process of the object, the basic motion configuration of the system includes that the external axis rotates unidirectionally at rotating speed ω and the robot performs a linear motion (nozzle scanning speed V) in axis direction. The centre of the nozzle keeps moving in the same plane aligned to the axis of the rotating substrate. The outlet of the nozzle maintains the specified stand-off distance to the surface and torch orientation at all points. The gun needs to be offset in each pass to compensate for the reduction in stand-off distance due to increasing part dimensions under deposition, thus ensuring constant process parameters, especially for depositing thick shell parts. The settings of rotational speed and torch scanning speed depend on the variation of the radius of the rotating substrate. For a substrate with a constant radius (e.g. a cylinder), the speed settings remain constant. For a substrate with varying radius, the tangential speed of the relative linear speed V_L between torch and substrate increases with the increase in radius. The torch scanning speed should therefore decrease as the radius increases to maintain the same increase in deposit thickness on the substrate (as shown in Figure 2). The torch scanning speed can be described by

$$V_T = \frac{R_1}{R_T} \cdot V_1 \,. \tag{1}$$

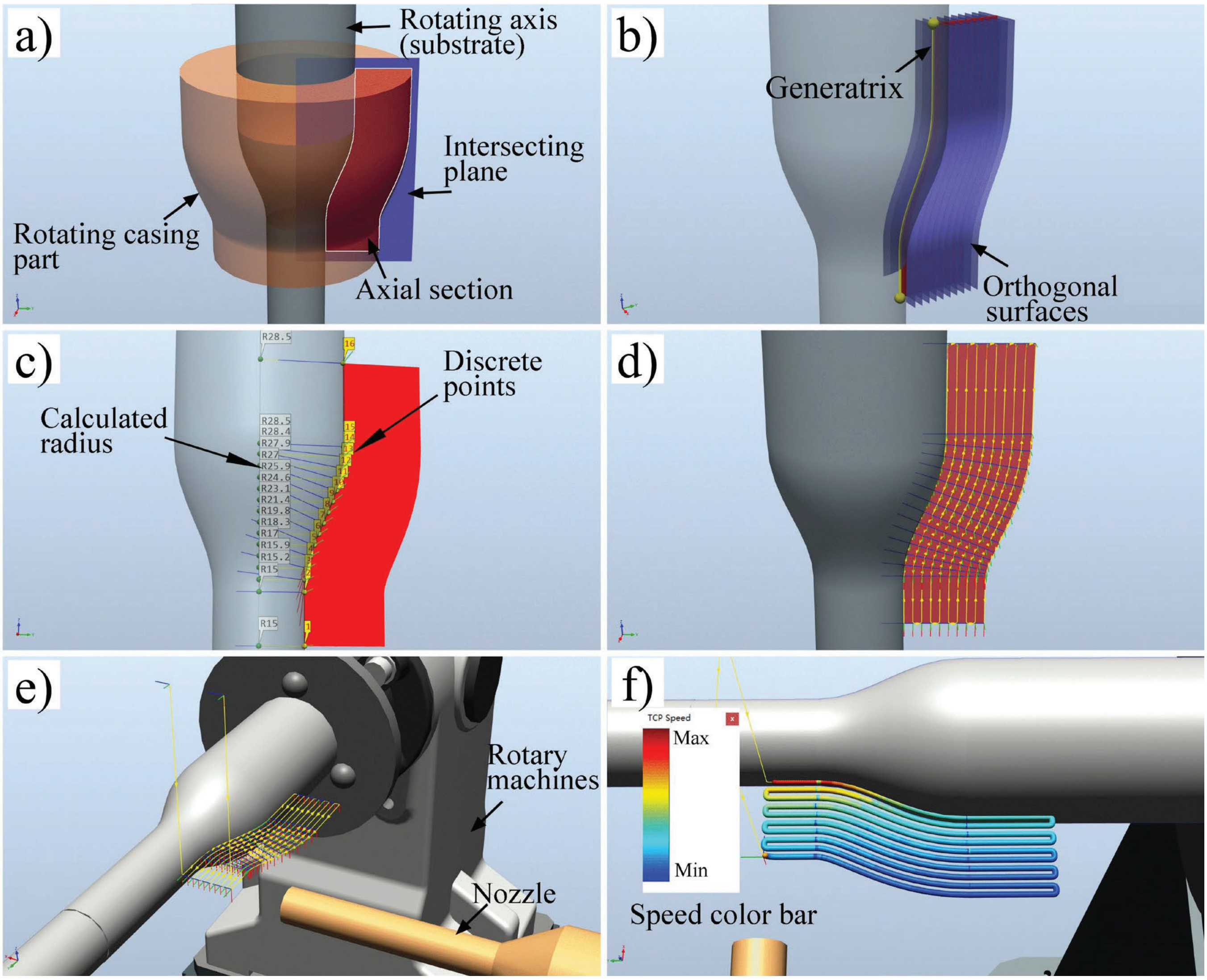
Here, V_1 is the torch scanning speed at radius R_1, defined as the reference speed and radius for the calculation of other torch scanning speeds. R_T is the corresponding radius at a different target point along the path. The ratio of R_1 and R_T is regarded as the adjustment factor of speed.



FIGURES 2: RELATION BETWEEN SETTING OF TORCH SCANNING SPEED AND SUBSTRATE RADIUS

B. Toolpath Planning for Rotational Symmetry Parts

Figure 3 illustrates the principle of toolpath planning and generation for casing objects with rotational symmetry. The first step is to obtain geometric data of the axial section of the rotating object. These can be obtained by using measured dimensions as input or by calculations from plane intersections in the CAD file of the object (as shown in Figure 3a). Then, the generatrix of the rotating substrate, i.e. the intersection line between the substrate and the obtained axial section, is selected to create an orthogonal surface (as shown in Figure 3b). This orthogonal surface is then off-set according to layer thickness to create a series of orthogonal surfaces that can completely cut the axial section. The values of layer thickness can be calculated empirically or obtained through experiments for a certain powder/substrate material system and adjusted process parameter sets. Based on Boolean operations, intersecting curves between the axial section and the orthogonal surfaces can be obtained. Afterwards, each intersecting curve is discretized into points. In general, for straight-line segments only respective endpoints are needed. For curved segments, a tighter distribution of discrete points is required (as shown in Figure 3c). Each point contains information on index number, position, direction, and the radius of the substrate at the corresponding position. The orientation of each point is perpendicular to the surface of the substrate or the already buildup deposit. The axis radius information of each point is used for the automatic speed calibration after the subsequent setting of the torch scanning speed. Finally, a continuous toolpath can be created by linking each target in sequence (as shown in Figure 3d). The corresponding robot motion code can be automatically created and simulated in the virtual environment of robot (as shown in Figure 3e). Based on the previously developed method of robot kinematic analyses and visualization [11], Figure 3f shows that the torch scanning speed is executed in a preset way, i.e. the torch scanning speed decreases as the radius increases. A script is developed based on the aforementioned principles and methods and can automatically generate toolpaths for various rotary casing objects, as depicted in Figure 4.



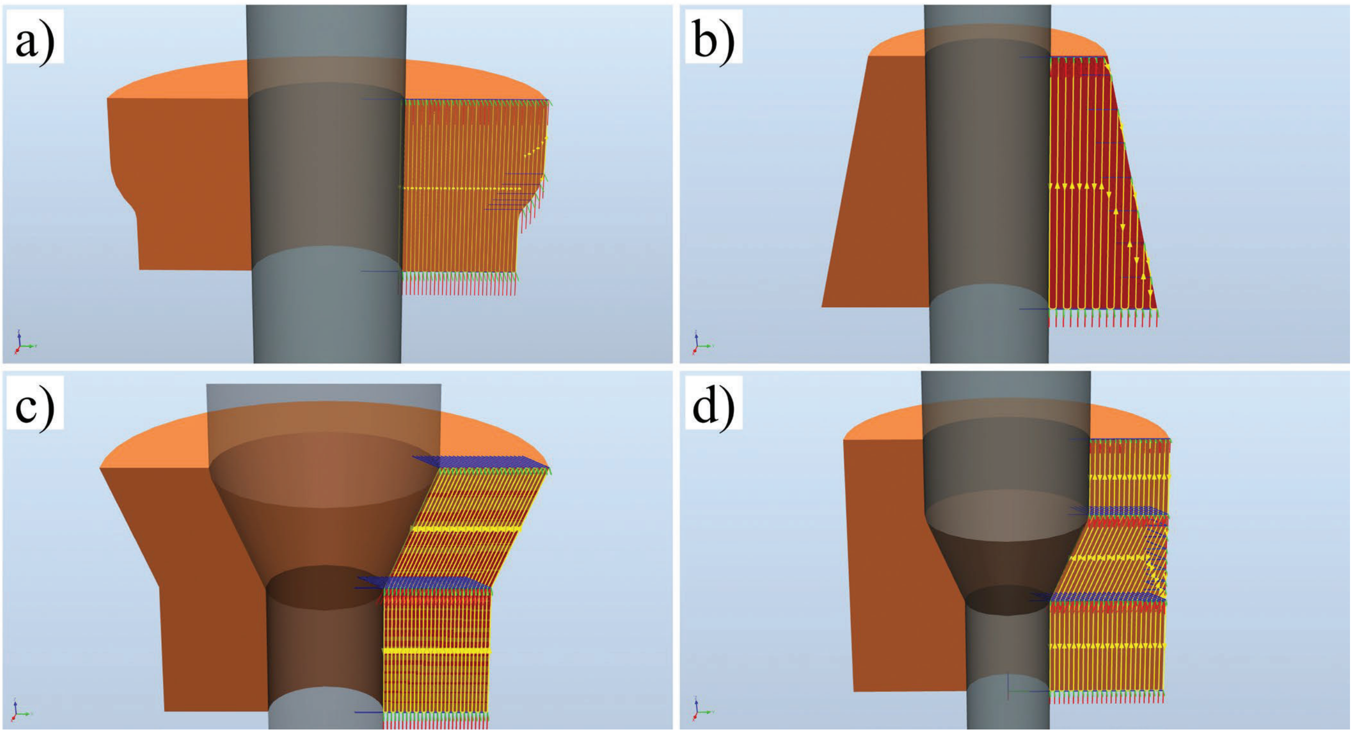
Figures 3: Principles of the toolpath planning approach for objects with rotational symmetry: (a) obtaining axial sections, (b) creating of orthogonal planes based on the generatrix, (c) discrete points with the information of their index number and the radius of the substrate at their corresponding position, (d) ordering and connection of points, (e) toolpath simulation, and (f) torch scanning speed variation (for interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article)

IV. SUMMARY AND OUTLOOK

In this work, a general method for CSAM toolpath planning and implementation for rotationally symmetric casing parts is presented. This method comprehensively considers the characteristics of cold spray, the robot kinematics, and the geometry of the workpiece, enabling the automatic and accurate creation of a desired toolpath through customized scripts. Robot kinematics simulations have demonstrated the feasibility of this method. Further validation and optimization will be pursued through specific case studies. Additionally, efforts will be made to integrate and coordinate other sub-processes, such as online monitoring and diagnostics as well as subtractive machining techniques to exert the full potential of cold spray additive manufacturing in shape building.

ACKNOWLEDGEMENT

The authors acknowledge the financial support in the frame of the project "CORE – Computerized Refurbishment" funded by dtec.bw – Digitalization and Technology Research Center of the Bundeswehr. Digitalization and Technology Research Center of the Bundeswehr is a scientific centre jointly supported by the Universities of the Federal Armed Forces in Hamburg and Munich and is part of the German government's economic stimulus program to overcome the COVID-19 crisis. It is subject to academic self-administration. The funds within dtec.bw for both universities of the Federal Armed Forces finance research projects and projects for knowledge and technology transfer. dtec.bw is funded by the European Union – NextGenerationEU.



FIGURES 4: TOOLPATHS FOR VARIOUS ROTATING CASING PARTS

REFERENCES

[1] H. Assadi, H. Kreye, F. Gärtner, and T. Klassen, "Cold spraying–A materials perspective," *Acta Materialia*, vol. 116, pp. 382–407, 2016.

[2] F. Gärtner, T. Stoltenhoff, T. Schmidt, and H. Kreye, "The cold spray process and its potential for industrial applications," *Journal of Thermal Spray Technology*, vol. 15, pp. 223–232, 2006.

[3] H. Wu *et al.*, "Stable layer-building strategy to enhance cold-spray-based additive manufacturing," *Additive Manufacturing*, vol. 35, p. 101356, 2020.

[4] F. Gärtner, A. List, S. Nielsen, H. Wu, Z. Arabgol, L.Wiehler, et al. Computerized Refurbishment, dtec.bw-Beiträge der Helmut-Schmidt-Universität / Universität der Bundeswehr Hamburg: Forschungsaktivitäten im Zentrum für Digitalisierungs- und Technologieforschung der Bundeswehr dtec.bw, 1(2022) 9–19.

[5] M. Lewke, H. Wu, A. List, F. Gärtner, T. Klassen, and A. Fay, "Automated Trajectory Planning and Analytical Improvement for Automated Repair by Robot-Guided Cold Spray," *J Therm Spray Tech*, Dec. 2023, doi: 10.1007/s11666-023-01697-w.

[6] F. Ortega, A. Sova, M. D. Monzón, M. D. Marrero, A. N. Benítez, and P. Bertrand, "Combination of electroforming and cold gas dynamic spray for fabrication of rotational moulds: feasibility study," *The International Journal of Advanced Manufacturing Technology*, vol. 76, no. 5, pp. 1243–1251, 2015.

[7] J.-M. Lamarre and F. Bernier, "Permanent magnets produced by cold spray additive manufacturing for electric engines," *Journal of Thermal Spray Technology*, vol. 28, pp. 1709–1717, 2019.

[8] "Additive manufacturing Ti-6Al-4V." Accessed: Jun. 26, 2024. [Online]. Available: https://impact-innovations.com/en/applications/cold-spray-additive-manufacturing-ti-6al-4v/

[9] "Additive manufacturing rocket nozzle." Accessed: Jun. 26, 2024. [Online]. Available: https://impact-innovations.com/en/applications/rocket-nozzle/

[10] H. Wu *et al.*, "A new approach to simulate coating thickness in cold spray," *Surface and Coatings Technology*, vol. 382, p. 125151, 2020.

[11] H. Wu *et al.*, "Generic implementation of path design for spray deposition: Programming schemes, processing and characterization for cold spraying," *Surface and Coatings Technology*, vol. 458, p. 129368, 2023.