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Wire arc additive manufacturing of parts with direct programming: Some examples

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Abstract - In this study, we demonstrate how direct programming (without slicing) can be used to print increasingly complex parts using Wire Arc Additive Manufacturing. The first example is the printing of a powder container for hot isostatic pressing (HIP) of powder. For this, a solid circular bottom was printed first with a spiral trajectory. Then, a hollow cylinder is manufactured. Finally, a dome-type top is added. In this application, the manufactured hollow part is then filled with powder and subjected to HIP to create a solid part from the corresponding hollow preform. The final example is a simple volute for a compressor or turbine application. We will demonstrate how to efficiently print this type of part based on multiple rotations of elementary points, lines and curves.

Keywords: WAAM, AISI 316L, HIP

1. Introduction

Wire arc additive manufacturing has become an efficient way to print near net shape components. Most of the time, works performed in research studies by universities/researchers consider simple geometries, such as flat walls, and focuses on investigating the materials properties. Meanwhile, some SMEs are developing efficient software solutions that allow for the printing of complex parts for industrial applications. For a few years, an intermediate solution has been developed at the ICB laboratory. This software solution enables the printing of a variety of parts (see Figure 1) by integrating slicing methods that automatically generate robot trajectories. Nevertheless, if slicing is probably the best way to generate robot trajectories for highly-complex parts, many parts do not require such tools. In particular, all industrial robots such as ABB, FANUC, YASKAWA, or KUKA own a proprietary programming language integrating elaborated mathematical functions, such as the trigonometric ones, and including loops, as in all conventional structured programming languages. For this reason, many parts can be printed by direct programming.

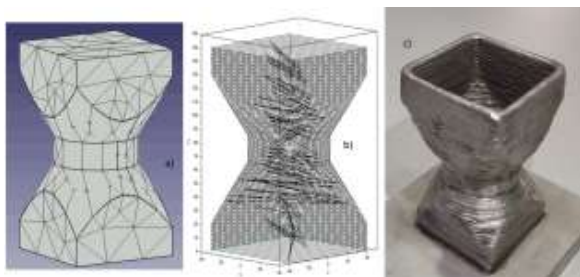


Figure 1. Example of hollow parts manufactured by WAAM (FRONIUS CMT mode), a) STL file, b) Robot trajectories from slicing, c) Printed part

2. Objectives and Results

The main objective of the present work is thus to show how Direct Programming may be used to print Near Net Shape parts by WAAM. For this, KRL (Kuka Robot Language) was used to provide accurate trajectories for a KR8 KUKA robot.

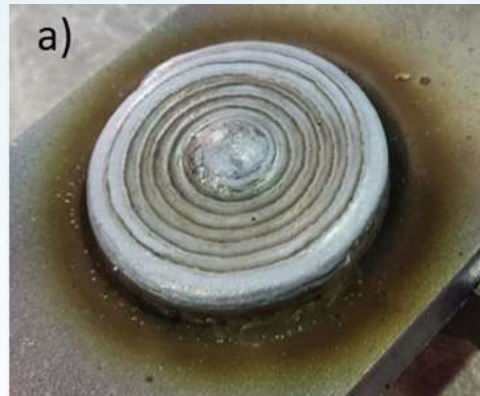


Figure 2. Example of solid cylinder manufactured by WAAM with a spiral trajectory (a few superposed layers) – FRONIUS CMT welding device

For example, the best way to print a solid cylinder consists in printing superposed layers deposited with a spiral trajectory (see Figure 2). The use of a slicer is not advised to print this type of part. Instead, the required robot trajectory may be simply defined using a few lines of coding, as:

$$x(t) = A t \cos(t)$$

$$y(t) = A t \sin(t)$$

in which A has to be estimated to get the correct value of the gap/distance between successive/juxtaposed beads. Please note that angles are given in degrees in KRL.

Printing of a hollow cylinder is also simple: in that case, a loop may be used to print superposed circular welds. For this, the definition of three vertex on the circle are sufficient. Alternatively, a single vertex can be defined, whereas the two others can be set by rotational transformation as:

$$\begin{bmatrix} x' \\ y' \\ z' \end{bmatrix} = \begin{bmatrix} \cos\theta & -\sin\theta & 0 \\ \sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ z \end{bmatrix}$$

This transformation allows rotating point $P1(x,y,z)$ by a θ angle. Superposition of a hundred of circular welds on the bottom shown in Fig. 2 was used to print the cylindrical part shown on Figure 3.



Figure 3. Example of hollow cylinder manufactured by WAAM on a bottom composed of spiral type layers such as that of Fig. 2.

Concerning the dome, printing a half-spherical dome on the basis of constant thickness slicing is probably impossible. Instead, a progressive refinement is required. The required refinement is illustrated on Figure 4. For this, it is assumed that the inclined thickness of each deposited weld bead remains unchanged. Results obtained with this strategy (Figure 3) were particularly encouraging.

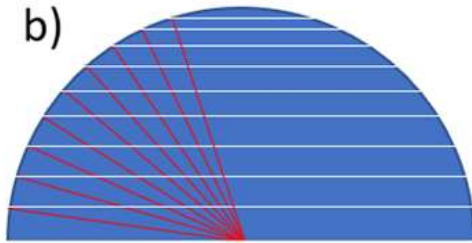


Figure 4: Principle of slicing refinement to print a half-spherical dome.

This type of hollow part (Figure 3) is almost ready for being used as capsule for the HIP sintering of powder, thus allowing providing a solid part from the present hollow one. For this type of process, the capsule is first filled with metallic powder on a vibrating tray, a vacuum draw is then performed, and the part is then sealed. The next step consists in applying Hot Isostatic Pressing (HIP) to the part, thus allowing to close all existing voids between the powder grains. Note that the WAAM capsule has to remain gastight during the whole HIP process, that consists in placing the part in a chamber filled with a high-pressure (200 MPa) high-temperature neutral gas such as argon. If the capsule remains perfectly gastight during the process, preventing the high-pressure argon propagating inside the capsule, the process results in a solid part (99.9% density) as shown on Figure 5 obtained after cutting and polishing.



Figure 5: Cross-section of a part after HIP of powder in a cylinder manufactured by WAAM.

This technology presently called WAAM-HIP is useful to get quickly solid parts from the corresponding hollow capsule manufactured by WAAM. It may represent an alternative to casting and forging for the manufacture of large metal components in the coming years, especially in the frame of the manufacture of components for new SMRs in the nuclear domain. The HIP press/facility recently installed in Le Creusot (QUINTUS QIH60-URC2) during September 2025 (Figure 6), was financed in the frame of ANR EQUIPEX+ CALHIPSO (Compression et Assemblage par HIP une Solution Innovante) under agreement ANR-21-ESRE-039, and will allow manufacturing solid parts with dimensions up to 1 m in height, and 420 mm in diameter. Since the powder is never melted but just sintered, the resulting grain size in this type of part is

extremely fine, thus improving the mechanical properties for a given material.



Figure 6: HIP facility available in Le Creusot, funded in the frame of the CALHIPSO EQUIPEX+ project.

3. Conclusion

The present study was devoted to show how direct programming in KRL language is useful to print quickly parts using Wire Arc Additive Manufacturing, and without the need of a slicer. A capsule devoted to the HIP sintering of powder was manufactured in a single afternoon. The HIP sintering of powder with a similar capsule was successful, and the suggested two-step process may represent an alternative to casting and forging for the manufacture of complex solid parts, especially in the nuclear domain. The advantage of the process is the extreme fineness of the microstructure achieved with this process in the core of the part composed of sintered powder. Up to now gastight capsules required by the HIP process are manufactured using conventional welding mechanic methods (including cutting, stamping and welding operations). The manufacturing of complex-shape capsules is thus time-consuming and may represent up to 45% of the cost of the component, including its removal after HIP [1]. WAAM printed capsules are expected to allow a huge reduction of the manufacturing time of the capsule, which is a brake in the development of the technology. Finally, methods used to print the volute mentioned in the abstract with Direct programming, will be exposed/detailed during the conference.

References

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