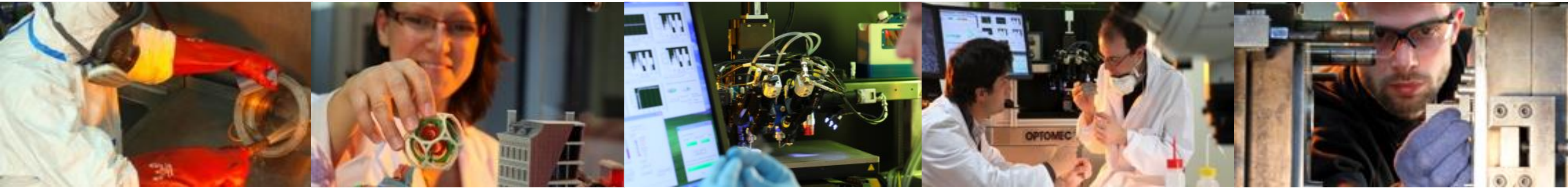


L-PBF vs. LMD – Case study using a generalised rotor

The INSIDE Metal AM project

Introduction

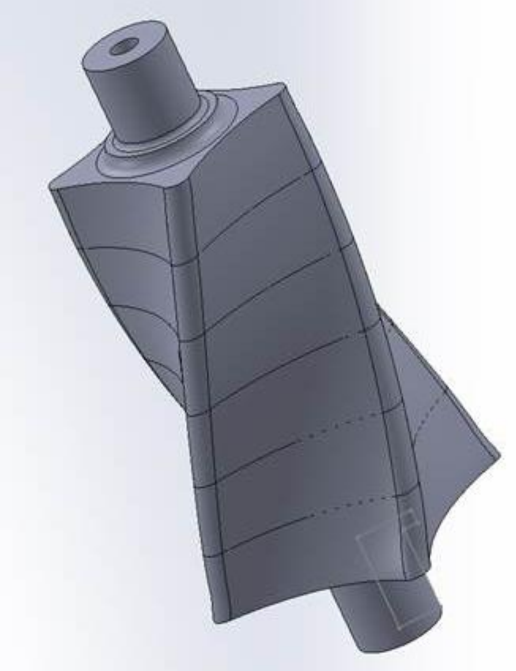
The INSIDE Metal AM project was started in 2018 in order to support the uptake of 3D printing with steel by the Belgian industry. Therefore, the aim was to be able to provide guidance along the entire process chain, starting from raw materials to finishing of the part. This was done through a combination of applied research and the realization of a number of industrial demonstrators. The project focused on three different AM technologies: Laser Powder Bed Fusion (L-PBF), Laser Metal Deposition (LMD) and Wire Arc Additive Manufacturing (WAAM). A number of different steels were used in the project: 316L, 17-4PH, H11, 2209 and S355. The topics covered by the project are materials selection and handling, the process-structure-property relationships and post-processing (including heat treatment and surface post-processing).

Here, one of the demonstrator parts realised within the INSIDE Metal AM project is presented. A rotor design was developed within the project and printed using two different techniques: L-PBF and LMD. A comparison between both technologies is made and the comparison to conventional manufacturing is briefly discussed.

This project received support from the Strategic Initiative Materials (SIM Flandres) and het Vlaams Agentschap voor Innoveren & Ondernemen (Vlaio).

Project partners: Sirris, CRM, BIL

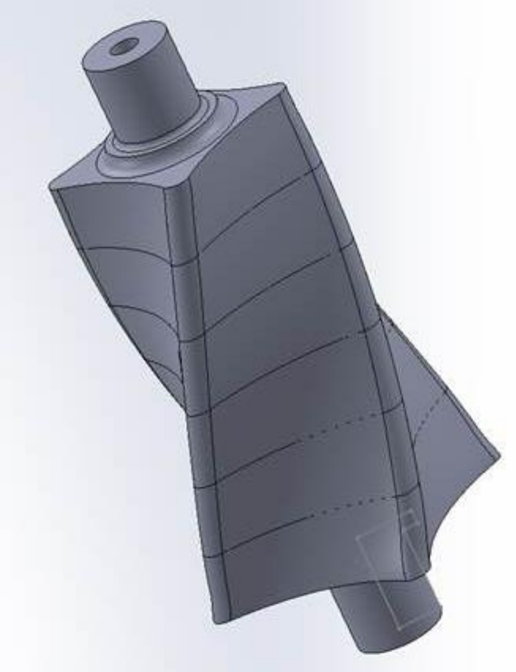
Design



This demonstrator was designed as a showcase to compare the possibilities of two AM techniques: LMD and L-PBF. The rotor was designed in such a way that it adresses a number of particular challenges.

1. The rotor is skewed from top to bottom (i.e. the bottom has a larger diameter).
2. The top and bottom are rotated with respect to one another, resulting in a double curved surface. During the design phase, the degree of rotation was chosen in such a way that the amount of overhang is limited to what is printable using LMD.
3. The axis is hollow and opens to the hollow interior of the rotor, this allows the powder to be removed in the case of L-PBF.
4. The inside of the rotor is reinforced using an internal structure.
5. No internal cooling, air of lubrication channels are included in order to allow the comparison between LMD (where such channels cannot easily be created) and L-PBF.

Design



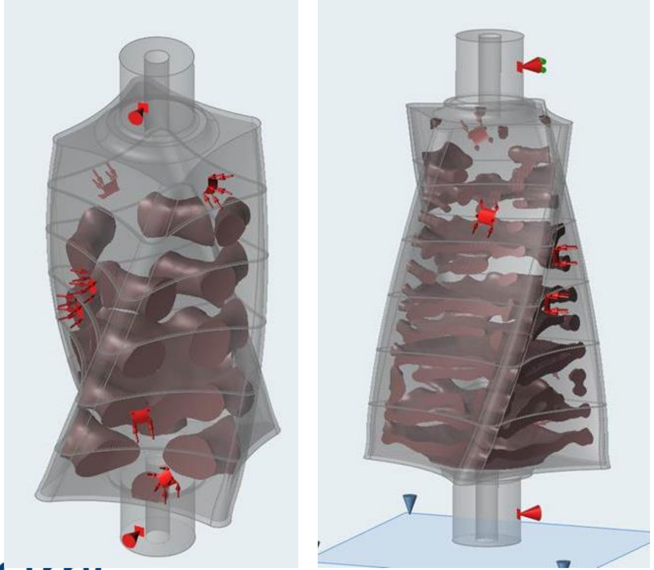
Ø Bottom: 100 mm
Height rotor: 155 mm
Total height: 225 mm

Rotation top vs. bottom: 70°
Bevel bottom to top: 2°

Skin thickness: 3 mm

Design

Topology optimization



Using Topology Optimisation (TO), the internal structure of the rotor can be designed, for example to minize the weight, will still being able to bear the loads imposed during service.

1. **Topology optimization (TO) linked to part orientation in AM machine**: As an example, the brown structures cannot be printed with the part orientation as displayed, without adding additional support structures. TO should therefore also take into account the print orientation.
2. **Requires realistic load case**: The examples on the side are based on a simple load case for illustration purposes. Because no realistic load-case exists for the demo part designed in the project, no in-depth TO was performed.
3. **Importance of boundary conditions**: As an example, the two images on the right were obtained using different settings of the maximum segment thickness.

Design

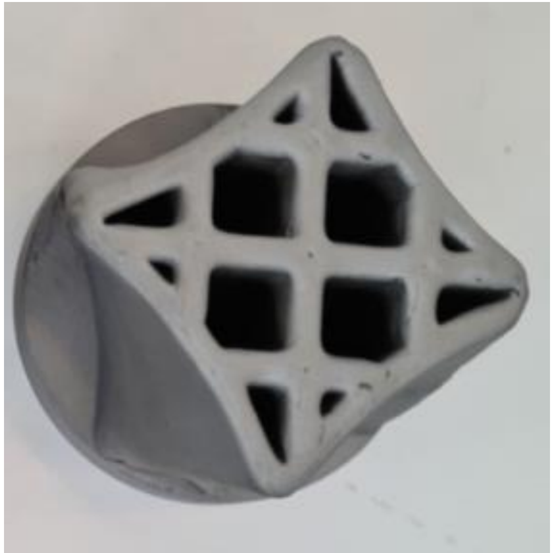
Lattice vs. topology optimization (L-PBF)

An alternative to TO is using an internal lattice. This is the approach followed here, as no realistic load case existed to perform the TO.

For illustration purposes, a graded lattice was used in the demo part. The lattice is denser and has thicker legs in the bottom as compared to the top. Introducing gradients in the lattice allows to optimize the support structure for non-homogeneous external loads. A few remarks:

1. Different types of internal lattice exist. The optima choice will depend on the application.
2. The orientation of the lattice needs to be adapted depending on the orientation of the part with respect to the build direction, in order to allow printing of the lattice without additional supports.
3. A lattice like the one chosen here may not be ideal for load bearing purposes, because of the introduction of stress concentrators.

Design



Internal structure in LMD

Also in LMD an internal support structure was added.

The complexity that can be achieved using LMD is much smaller as compared to L-PBF. The type of lattice as used in the L-PBF part could thus not be used for the LMD part.

Job Configuration

Lessons learned from demonstrators – L-PBF

1. Importance of powder weight and layer thickness
2. Influence of part orientation
   1. Powder spreading
   2. Heat flow
   3. Surface quality
3. Necessity to heat treat
4. Importance of sieving under atmosphere
5. (Witness samples to be tested)

Job Configuration

Lessons learned from demonstrators – L-PBF

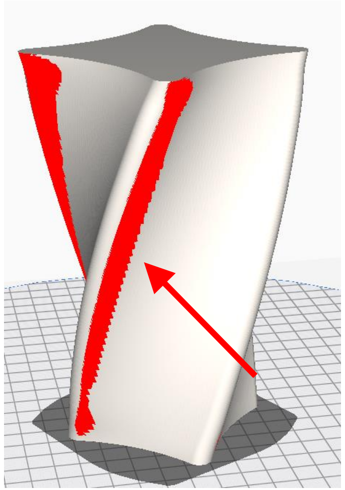
1. Reduce overhang
2. Avoid surface orientation close to the limit
3. Avoid large and long horizontal sections
4. Take care about thermal dissipation
5. Take care of powder removal
6. Powder spreading

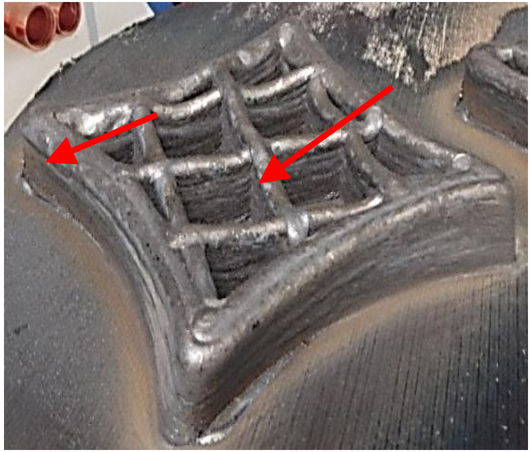
Main Lessons learned from the L-PBF demonstrator

1. ***Importance of powder weight and layer thickness:*** the machine used for printing had previously mainly been used for aluminium powders. Upon printing of the 17-4PH steel, the powder wiper came lose due to the powder being to heavy. The wiper had to be fixed more securely to avoid this problem.
2. ***Importance of part orientation:***
    1. *Avoid surface orientation close to the limit:* At an inclination of 45° from the vertical direction, an unacceptably rough down facing surface was observed.
    2. *Avoid large and long horizontal sections:* When printing the rotor in a completely vertical direction, the section to print changes radically when coming from shaft to the rotor itself. As a result a large layer has to be printed on the support structure, which leads to a rougher printed layer. It proved more difficult to spread powder evenly over this rough layer, resulting in a build failure.
    3. *Influence on thermal dissipation:* Higher tilts lead to a decreased heat removal through the part itself. Supports were added to compensate for this, based on experience with Ti, but this proved insufficient. More supports might have worked, but here the choice was made to work with smaller inclination to avoid a rough down facing surface. Overheating lead to defects near the top of the part (instability of melt pool/surface deformation).
3. ***Necessity to heat treat:*** In some builds (depending on part orientation), the part supports came loose from the build plate, clearly indicating the presence of residual stresses. In order to make sure that no deformation occurs when cutting parts of this size from their build plate, it is advised to perform a stress relief heat treatment prior to removal from the build plate.
4. ***Importance of sieving under atmosphere:*** At the location of the discoloration, recycled powder was fed into the machine. After noticing the discoloration, it was found that there was a problem with the protective gas enclosure during sieving, leading to an increased amount of oxidation. Tensile samples with a similar discoloration were found, but failure did not occur at that location on the sample.
5. ***Powder removal:*** The design is not ideal when it comes to removal of powder from inside the rotor.

Job Configuration

Lessons learned from demonstrators – LMD





1. Reduce overhang (e.g. 15° if 2D positioning)
2. Avoid “hot spots” (start positions, speeds…)
3. Optimize paths for intersections/filling
4. Optimize “cold” displacements to minimize powder waste

Additional technical information on LMD printing of the rotor is available in the document ‘LMD processing and testing’ on the project webpage.

https://www.sirris.be/nl/inside-metal-additive-manufacturing

Generalised rotor

L-PBF and LMD of 17-4PH steel

An example on technology selection: L-PBF vs. LMD

L-PBF

LMD

Total Height: 225mm
Ø 80-100mm

The following is a comparison based solely on our own experiences and best estimates!

Technology comparison

L-PBF

- Printed in a single step
- Printing is relatively slow (2 days > 14h, range depends on machine type and choice of print parameters, printing in this project was done using research machines)
- Approx. 20% dead time (recoating)
- Deposition: 50-150 g/h

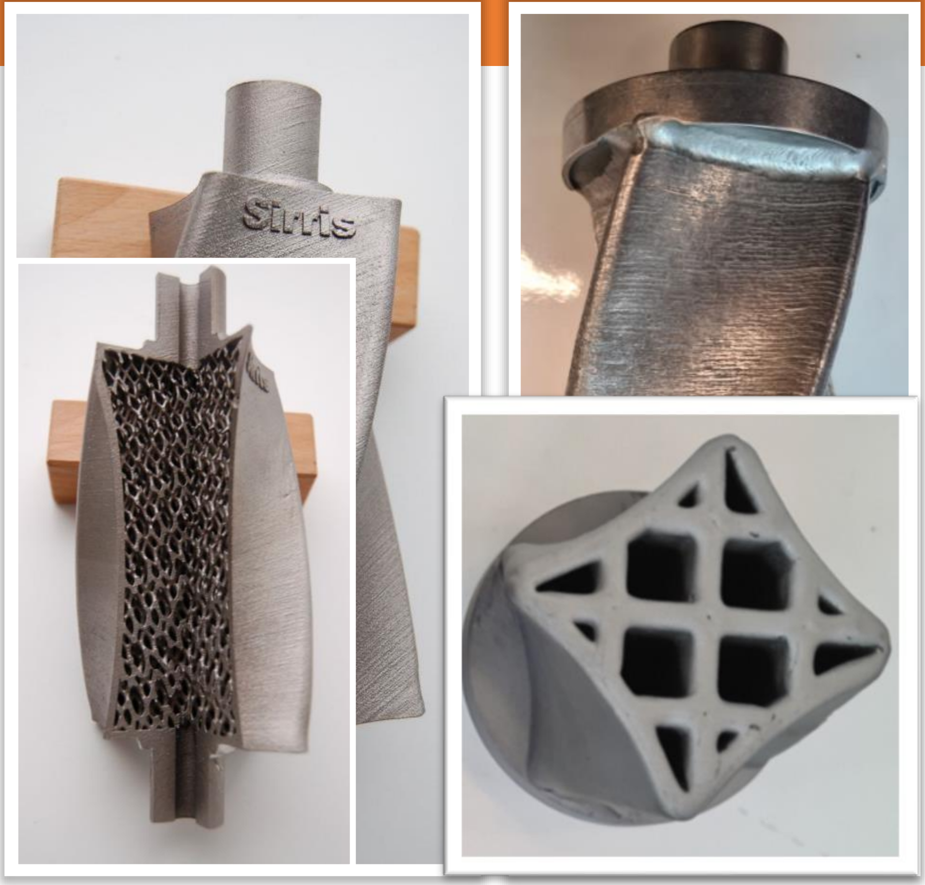
LMD

- Multi step process (top is welded on the printed part)
- Printing is fairly fast (11h > 8h possible with improved equipment, printing in this project was done using research machines)
- 50% dead time, large reduction possible when printing multiple parts simultaneously, one part can cool while other is being printed
- Deposition: 700 g/h

Technology comparison

L-PBF

- Overhangs up to 45°
- Walls: 3mm
- Internal structure can be very complex
- Fine, complex shaped cooling channels possible
- Layer thickness: 30-60µm (i.e. approx. 7000 layers for this part with 30µm layers)
- Post processing to reduce roughness, tolerances <0.1mm possible



LMD

- Overhangs, here: 20°. Large overhangs require skill and complex machine movement (manipulate the part is such a way that there is always sufficient material supporting the meltpool)
- Walls: 9mm
- Internal structure is kept more simple
- Holes can be left open to serve as cooling channels
- Layer thickness: 500µm
- Finishing in most cases by machining (tolerances 0.5-1mm)

Economic (cost) comparison

L-PBF

Main Cost elements

- Preparation time mainly in design phase
- Machine time (# of layers, material volume, print parameters)
- Material cost (powder cost and efficiency)
- Cleaning time (Support removal, Powder removal, Sand blasting)
- Post processing and Finishing

LMD

- Preparation time strongly scales with complexity (integrate in a robot or 5-axis machine)
- Machine time (cooling, start/stop, volume)
- Material cost (powder cost and efficiency, powder losses can be significant, but with a carefully tuned and equipped machine, powder efficiencies > 90% are obtained)
- Cleaning time
- Post processing and Finishing

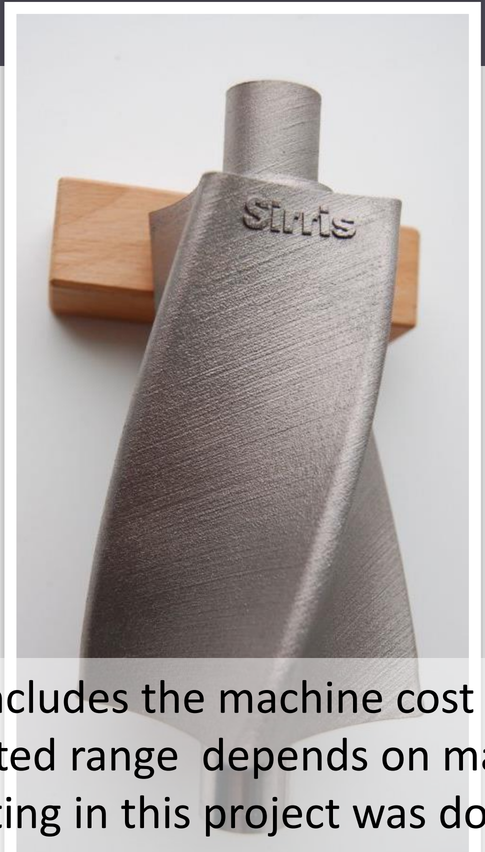
Economic (cost) comparison

L-PBF

Estimated build cost:
1000-2000 euro

Total material cost:
Cost of steel powder, approx.
50 euro/kg
±120 euro (part weight: 2 kg + powder losses)

Only limited influence of complexity on total cost.



LMD

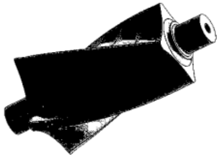
Estimated build cost:
800-1000 euro

Total material cost:
Cost of steel powder, approx.
50 euro/kg
550 euro (part weight: 5.5 kg + powder losses)

Larger influence of complexity on total cost (preparation time).

Here, build cost only includes the machine cost (i.e. mainly governed by build time-. The indicated range depends on machine type and choice of print parameters, printing in this project was done using research machines

Making the choice…



Even for a specific case, **the choice** between these two technologies **is not self evident**. A good knowledge of the application is required (domain expert), as well as a good understanding of the possibilities of each technology (AM expert).

The economic evaluation and comparison to conventional manufacturing depends on a great number of factors. It is therefore not possible to define a 'generic case' to compare AM technologies with each other or with conventional manufacturing.

Comparison to conventional manufacturing

(NNS casting + machining)

- Obsolete spare parts
- Single parts (vs. high cost for moulds), impact of number of parts
- Cooling/weight reduction
- Complexity

For the demonstrator discussed here, the most meaningful comparison would be a comparison to Near Net Shape casting (for example using the lost wax process). The cost of a non-finished cast part of high complexity and similar size as the ones printed here would typically be in the range of 100 euro. This clearly shows that part will typically not be replaced one-on-one by Additive Manufacturing.

One needs to use AM and the increased design freedom it offers to create new products with improved functionality. AM should be seen as an opportunity to rethink current part design and improve them, for example by:

1. Reducing weight (transport applications, components that need to be handled by people, reduction of inertia for fast moving components with a lot of starts/stops, etc.)
2. Adding channels/controlled porosity for cooling, lubrication, blowing of air through surfaces (non-stick applications), etc.
3. Integration of functionalities and part consolidation (from multiple parts to one part, reduction of assembly costs)

Other potential situation where AM can add value:

- Small number of parts needed (in the case of comparison to casting, the mould costs can be high)
- Production of spare parts (for example for which no moulds exist anymore)
- Shorter delivery times/shorter development times

It should be remarked that AM can also bring other difficulties such as a lack of internal expertise, still a smaller choice of materials, difficulty of qualification and certification, often more difficult to inspect due to complex shapes, etc. All of these are difficulties on which a lot of work is being done to overcome these barriers.

Residual stress measurement

Residual stress measurements have been performed on the printed rotor in as-built condition. The measurement method is based on X-ray diffraction.

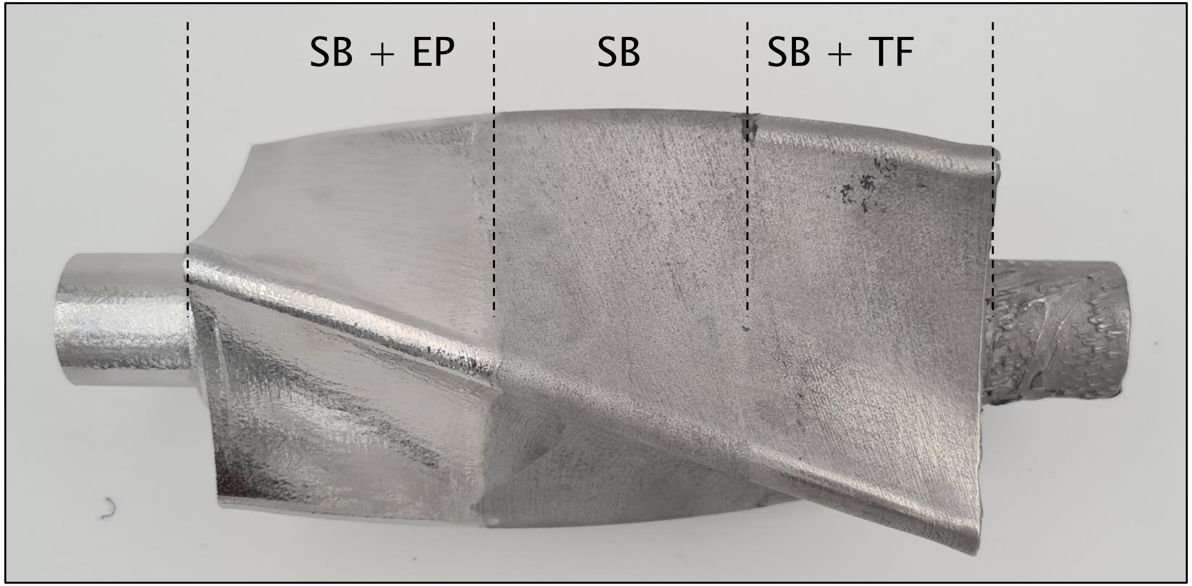
The residual stress on the top (last layer to solidify) are on the order of 400MPa (measured on the martensite phase). When measured on the side wall, the stresses appear to be much lower (<100MPa). However, there is also retained austenite in the material, where larger stresses were observed (>100MPa).

After sand-blasting, stresses in the surface become compressive (-250MPa).

A more detailed study of the measurement of residual stresses in AM parts using X-ray diffraction is underway but was not within the scope of this project.

Polishing of demonstrators

SLM rotor



- The whole part was sand-blasted.
- Tribofinishing and electropolishing were compared on both ends of the rotor.

For more information, see the document 'Surface finishing of L-PBF and LMD parts' on the project webpage. https://www.sirris.be/inside-metal-additive-manufacturing

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