INSIDE Metal AM – 3D Printing with Steel

White Paper

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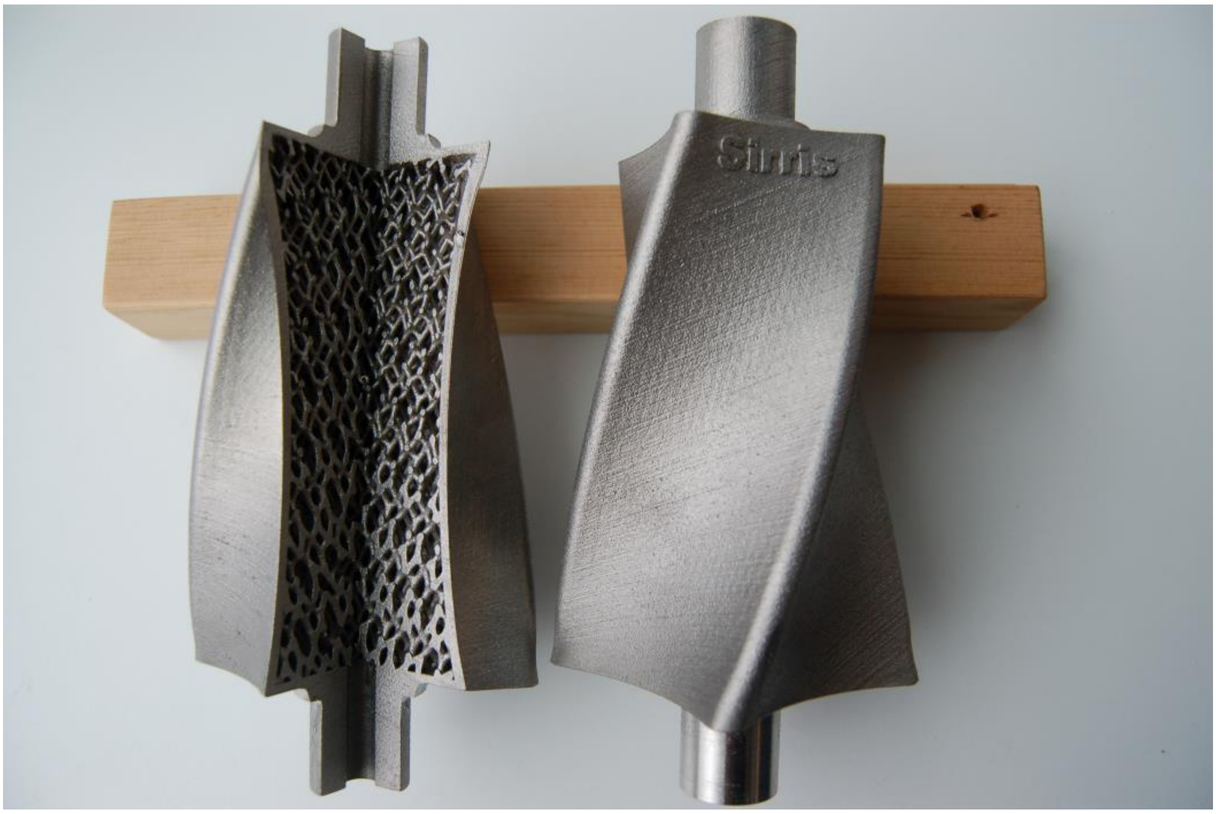
More information about this project can be found on: https://www.sirris.be/inside-metal-additive-manufacturing



Demonstrator parts printed using 17-4PH steel on an SLM250 machine.

Table of Content

1 Introduction – Questions to be answered

Metal 3D printing, or Metal Additive Manufacturing (Metal AM), has been around for more than 2 decades[1]. Although Metal AM has known a strong hype, the growth of the metal AM market has not followed the hype. The reason for this is a combination of both technological and economic challenges. The technological challenges include the availability and choice of materials, a good understanding of the material properties obtained and the required post-processing steps. From an economic point of view, the challenge is re-thinking designs in order to make use of the opportunities AM offers to add value to products and processes. Only in this way can a strong business case be realised where the higher cost of metal AM (as compared to conventional processing) is offset by the additional value offered by the design and manufacturing freedom.

The intention to start using AM can come after having seen applications that were developed in other industries or simply because of a conviction that your company could also profit from this new and exciting technology. But in order to actually apply metal AM, there may be a lot of challenges to overcome. In a recent survey performed by Flam3D[2], companies from different industries and sizes have stated that the “lack of internal expertise and know-how regarding AM” is an important obstacle for them to go ahead. Whether you want to print yourself, or work with a service provider, many questions may come to mind. What is the most suitable technology? What material to choose? What material properties to use in my design? Is heat treatment required? Do surfaces need to be post-treated?

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).

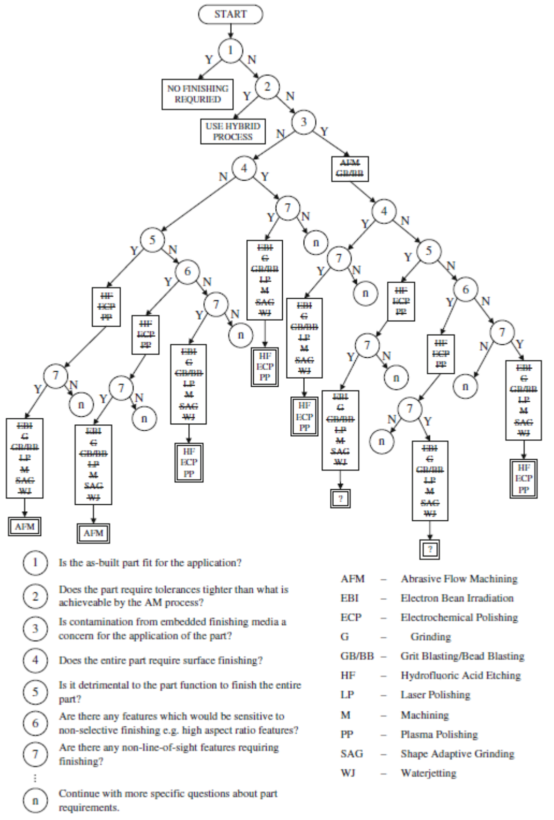


Figure 1: Example of a decision tree for surface post-processing technologies. Source: Gordon E.R. (2016) In: Sustainable Design and Manufacturing.

At the start of the project, the idea was to generate a number of flow charts or decision trees that could be used in the selection of appropriate materials and technologies. An example of a decision tree from literature is shown in Figure 1. Although such flow charts and decision trees can provide a first insight, we quickly came to realise that they cannot capture all the subtle nuances that are important in the selection of the most appropriate technology. Nor does it help you to realise important application dependent difference. They can therefore lead to a sub-optimal choice. In addition, the technology

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[1] https://www.asme.org/topics-resources/content/infographic-the-history-of-3d-printing, consulted February 2021.

[2] https://www.flam3d.be/hoe-ziet-de-groei-van-3d-printing-eruit/, consulted February 2021.

evolves so rapidly, with new materials and technologies coming to market every month, that flow charts and decision trees quickly become outdates if they are not regularly updated. The conclusion therefore is that a case-by-case approach is required, based on experience and knowledge of both the application and the AM technology.

This white paper is an effort to share the knowledge and experience gained in the INSIDE Metal AM project with a broad public. The information contained here is based both on process and material research and the realization of three industrial demonstrators. In this white paper, that information is summarized based on a number of questions, answered using the knowledge developed during the project. Where more detailed reports of the project results exist, reference is made to these reports, which are also freely available from the project webpage[3]. Below is a list of the questions we have tried to answer.

In case the information in this white paper and the additional reports available online doesn't answer your questions, or if you want to give feedback on the reports, discuss your ideas or specific cases, the reader is welcome to contact the authors.

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[3] https://www.sirris.be/inside-metal-additive-manufacturing

2 Powders for L-PBF and LMD – Selection and Handling

Steel powders with various chemical compositions are available on the market. Most of these powders are produced by means of gas atomisation. When selecting a powder or material for printing, the first consideration is the required properties of the printed part (mechanical, corrosion, bio compatibility, wear resistance, etc.) A second factor that needs to be considered is how easy or difficult it is to print the material. As a third element the amount of support available from machine suppliers should be evaluated. Especially for powder bed printing this can be relevant, as optimisation of print parameters can be a costly and time consuming undertaking.

When making a selection based on material properties, it is important to not only consider the as-build properties, but also the potential improvement in properties as a result of post-processing (heat treatment, nitriding, hardening, etc.). One should therefore carefully check the data presented in material datasheets and if necessary request more information on the state of the material for which the properties are given.

The Q&A mentioned below are an overview of the main lessons learned within the project. More detailed information can be found on the project webpage[4] *in the documents 'Aanbod en selectie van printmaterialen' and 'Quality of powders for AM'.*

What types of steel powder are available for L-PBF and LMD?

The number of off-the-shelf steel powders for L-PBF and LMD is still limited. The makes the selection of a steel powder still a relatively straight-forward exercise. The difference in cost between various steel types is limited, because the cost is mainly determined by the high cost of the production process (typically gas atomization) and less by the chemical composition. Typical costs for steel powder range from 40-80 euro/kg. Because of the small differences in cost, the material with the best possible properties can often be chosen. Moreover, using a higher strength material, may results in thinner walls being possible, thereby reducing printing time and overall part cost. It may even become interesting to consider all-together different materials such as titanium or nickel based alloys.

316L	CX
304	BLDRmetal L-40
H11/H13	M789
M300	Corrax
15-5PH	M3
17-4PH	Invar36
CL 91RW	

The most prominent steel types used for L-PBF and LMD are given in the table to the right. An overview of the composition, properties and suppliers of most typical steels is given in project report 'Aanbod en selectie van printmaterialen' on the project webpage.

Tailored powder compositions are offered on request by many powder suppliers. In this case a batch of typically min. 25-50kg of a specific composition is produced. Within Belgium it is also possible to collaborate with the KULeuven, department of Materials Engineering, or the UCL, department Materials and process engineering, who each have an atomization unit available for the production of small quantities of powder. Be aware that not only the cost of the powder will be higher, but that there is also a significant research effort that goes in to process optimization and material characterization.

What are the most important characteristics to take into account when selecting powders?

The first characteristic is off course the chemical composition. Small changes (<0.1wt%) in composition, especially of minor alloying elements like Nb, Cu, V, etc. can result in significant changes of the material properties. It is therefore important to always request the test certificate of the powder batch. However, also other characteristics play an important role in the print process, such as particle shape and size distribution, especially due to an impact on the powder flowability. For most L-PBF machines, a very good flowability is required. For LMD processes, the tolerance towards powders with reduced flowability is higher. LMD powders are also somewhat larger in size (typical

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[4] https://www.sirris.be/inside-metal-additive-manufacturing

distributions are 45-180µm, 45-150µm, 45-105µm and 53-180µm) than L-PBF powders (typically 15-45µm).

And additional important consideration is the presence of gas inclusions in the powder itself. Due to the very high melting and solidification rates, gas bubbles that are present in the powder will typically not be able to escape upon melting and be trapped in the manufactured part as gas porosity.

Also the atomization gas used can have an influence on the final part properties. 17-4PH steel, atomised under nitrogen atmosphere will have a higher nitrogen content (0.1-0.15wt%). Literature suggest that nitrogen can limit the transformation to martensite, resulting in lower hardness values. The results obtained during this project certainly don't this observation.

How can the powder quality be determined and maintained?

Powder transport, handling and recycling may cause drift in powder quality and properties by changing humidity levels, oxidation levels, particle shapes and particle size distributions. This has a direct impact on flowability and spreading of the powder and therefore also on part quality. But there can also be an indirect impact by resulting in increased part porosity and oxide inclusions. For 17-4PH it was observed that the average particle size increased after use, which had a positive effect on the flowability improved (shorter times in Hall Flow). However, for other powders (e.g. 316L), powder recycling was seen to reduce the flowability, even after mixing with virgin powder. For 17-4PH, it was further observed that using a powder batch sieved under air, resulted in a discoloration of the printed part. Mastery of the full chain of material handling is therefore mandatory to reach good quality on final part and powder properties. This includes printing, sieving, mixing, handling and storage.

Powder testing is critical to track powder quality over time and guarantee part quality. The testing itself can be cumbersome and time consuming. In order to speed up production flows, a two-step process, based on fast response granulometric techniques was adopted in this project. It was found that compaction curves (automated tap density) give relevant information on oxidation, humidity, size distribution, spreadability and segregation and can be used as a fast method to detect anomalies (density vs. number of taps curve shifts up/down). In case an anomaly is detected, the powder batch can be temporarily taken out of rotation and further investigated to determine the cause of the anomaly and the possible impact on build part properties.

Powder should be extensively characterised when it arrives, and a reference compaction curve determined. The batch should be rejected if the properties (for example particle size distribution or flowability) are not within the specifications. Detection of drift over time can then be performed using the fast method of compaction curve determination. It should be remarked that the compaction curves are sensitive to the global effect of the process itself. I.e. samples taken from different locations in the process give different results (main tank - ref, recoater, build chamber, overflow). A good sampling procedure should therefore be put in place and respected. By building up a history for your printing equipment in your environment and threshold for powder acceptance based on compaction curves can be further fine-tuned.

3 Wires for WAAM – Selection and Handling

WAAM processes

Currently there are different arc based processes being used in order to perform Wire-Arc Additive Manufacturing (WAAM). These can be divided in 2 families i.e. processes with a consumable electrode (like GMAW) and the ones with a non-consumable electrode (like GTAW, PAW). Both approaches are being used for WAAM but they might require slightly different specifications for the wire. Theoretically all these processes could use the same wire as long as the wire feeders support the applied wire (dimensions, tolerances, weight, spool type, …) and correct feeding is guaranteed (robustness). In both cases the chemical composition will be similar, there might however be a slightly different optimization in order to compensate for differences in heat input, element burn-off etc. In case of consumable electrodes, the wire is also responsible for drawing and maintaining the electric arc. This would typically accentuate (additional) aspects such as easy arc ignition, arc stability, robust transmission of current from contact tube to wire etc.

More process related information can be found in the document 'Wire selection for WAAM: Quality insights' on the project webpage[5]*.*

Wire selection and handing

Filler wires for welding have been around for decades and the patent for using a GMAW-like process for metal deposition to make 3D geometry was already filed in 1925. However, investigations regarding WAAM have been slowly increasing since the 1990's and the first commercial machines are on the market since about 5 years (e.g. Gefertec 3DMP technology). The first guidelines for product and process certification (DNV-GL, Lloyds …) are also very recent. No wonder that the guidelines and standards regarding the wires have also been published recently or are still under development. Currently rather limited information is available e.g. PAS 6010:2019 (Publicly Available Specification – "Wire for DED processes in AM") published by the BSI. These documents are nearly all based on the standards, guidelines and best practices on filler wires for welding purposes. Some specific remarks for WAAM are include, e.g. the actual chemical wire composition is to be agreed with the customer, but basically no specific WAAM values etc. are available.

What kind of wires are available for WAAM application?

Most of the wires currently used for investigation purposes and WAAM production are being supplied by well-known welding wire manufacturers such as ESAB, Lincoln, Böhler etc. Theoretically solid as well as (metal) cored wires could be used but in practice mostly solid wires are applied (often diam. 0.8mm to 1.2mm). Currently only one specific manufacturer of WAAM wire is known i.e. Böhler-Voestalpine ("3Dprint" solid wire). These high quality wires are claimed to have metallurgical and surface properties that are optimized for WAAM (robust processing and many consecutive heating cycles). Also, certain wire manufacturers propose wires for automatic welding purposes. The composition and manufacturing of these wire have been optimized. Companies with enough metallurgical experience or with a specific application could also directly contact certain welding wire manufacturers that have production equipment for wire prototyping.

What composition to select for a WAAM application and what is available?

As most of the currently used wires for WAAM are filler materials for welding, quite a large selection of steels, Ti-alloys, Ni-alloys, Al-alloys etc. are available with quite standardized compositions. Since typical WAAM applications would be a substitute for certain cast or forged parts, some of the available "3Dprint" wires are actually more aligned with a casting/forging chemical composition (e.g. 2205 duplex steel) instead of the filler wire composition that would be typically used for welding such parts (e.g. 2209 duplex steel). In general, welding wires guarantee that when welded correctly, they assure a sound connection for parts of a certain composition used in a certain application. The composition used for welding is therefore typically not the same as the base metal e.g. S355 steel is welded with a filler material that is overmatching (rather having S420 – S460 characteristics). In some cases the filler wires are even very different from the base metal e.g. welding of Hardox (≈ hardened C-Mn steel) with an austenitic filler wire. For most of the welding wires the mechanical characteristics after welding are also made available by the manufacturer. It has to be taken into account that those values are obtained under processing conditions that are typically quite different from WAAM conditions (different heat input, amount of dilution with base metal, effect of multiple heat cycles etc.). Furthermore, depending on metallurgy, part size etc. a post WAAM heat treatment could be applied in order to better align the obtained material characteristics with the required part performance. Also the use of 2 or more wires being deposited at the same time for obtaining the required composition

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[5] https://www.sirris.be/inside-metal-additive-manufacturing

could be considered (some experimental developments have been done that way for aluminium alloys).
Another approach would be to analyse the initial part design and requirements so that after redesign, specification update, alternative heat treatments etc. using a standard welding wire composition would be acceptable for the final performance.

What are the quality requirements for a WAAM wire?
The recent developments in WAAM, as is the case for additive manufacturing in general, require that standards are developed for quality assurance. As mentioned before filler materials for welding have been used as a baseline e.g. PAS 6010, with some minor additions for WAAM processing. The bottom line is that quality welding wires from known manufacturers, which typically have far better characteristics than the requirements specified in the standard, with an agreed composition and well thought packaging would be a suitable wire for WAAM.

Typically the following aspects are mentioned in new guidelines and preliminary standards:

- The wire composition is to be
  - homogeneous throughout the length & section (e.g. element distribution for cored wires)
  - tested acc. to appropriate analytical techniques (cfr. established/published methods)
  - agreed manufacturer/supplier and customer (permissible/required % of alloying elements)
- Dimensions and tolerances of wires, spools etc. are a copy of welding wire specifications.
- The cast and helix (important quality characteristics of any welding) should be such that
  - deposition of material is not adversely affected (robust processing)
  - the wire is suitable for uniform uninterrupted feeding
  - they follows welding filler material standards (e.g. EN ISO 544)
- An adequate surface and internal wire condition should be assured i.e.
  - free from contamination and surface defects with potential adverse effect
  - free of internal defects (porosity/µ-impurities) with potential adverse effect
  - suitable for uniform uninterrupted feeding
- An acceptable marking and packaging approach would ensure
  - durable marking on the spool, on the outside of each smallest package …
  - an ID that is traceable to unique manufacturer/supplier/product (name, batch …)
  - that when transported, handled, dry stored etc. damage, contamination, deterioration etc. to the wire will not occur
- Quality and performance testing should be based on accepted methods (cfr welding consumables & materials testing) and performed on representative samples (deposit based on agreed process parameters…)

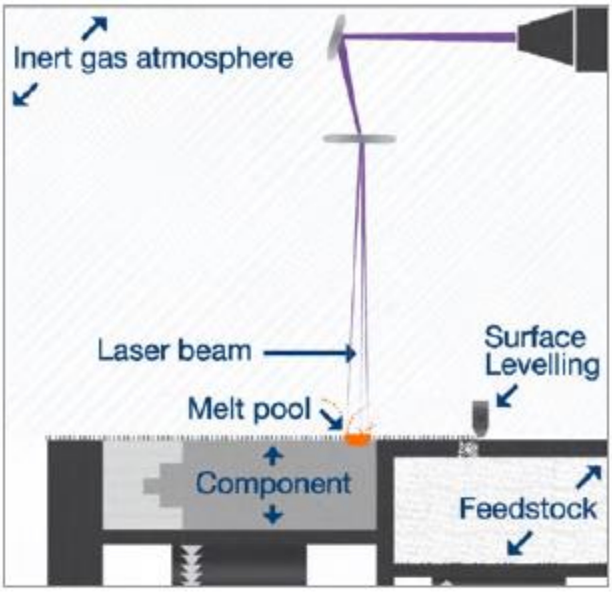
What about the cost of WAAM wire?
The cost for DED wire is considerably lower than for powders of the same composition. When comparing the prices of standard welding wire with materials sold as “WAAM wire” the cost can be quite different. Depending on the material type and grade some materials are produced in larger quantities than others, leading to a different production cost per kg. Also there are additional research and quality assurance cost that are probably added to that. These differences in manufacturing and marketing, since it is branded as a new and superior type of wire, can make steel WAAM wire anywhere from maybe 10% to 50% more expensive depending on the composition. It seems that for more “noble” compositions this effect is less, probably because the actual material cost becomes more important. However, this difference in cost is potentially irrelevant when taking into account the total project cost, when depositing relatively little material and/or when the process is much more robust (avoiding standstill, intermediate cleaning and possible rework). Welding wires typically have

prices in the range from 2.5€/kg (basic structural steel) to 25€/kg (specific duplex steel) and even higher for special compositions.

4 L-PBF and heat treatment of 17-4 PH and H11 steel

Laser Powder Bed Fusion (L-PBF) is a AM technology based on spreading a layer of powder and melting the powder in those locations where the part is to be build. By repeating this layer by layer, a 3D part is gradually being manufactured. Typical layer thicknesses for L-PBF are 30 or 60µm. Typical deposition speeds that can be obtained with steel are in the range of 50-250 g/h, with geometrical tolerances <0.1mm and typical surface roughness 5-15µm Ra. Within the project, an SLM250 machine was used.

The main focus of the project was on the heat-treatable 17-4PH steel, as this material received the highest interest from the industrial user group. Most of the information below therefore pertains to 17-4PH. However, a limited investigation of 3D printed H11 steel was also performed.



Source : Lloyd's Register & TWI Ltd

The Q&A mentioned below are an overview of the lessons learned within the project using 17-4PH steel. More information on L-PBF and heat treatment of 17-4PH steel can be found in the project report 'L-PBF and Heat Treatment of 17-4PH steel' on the project webpage[6]. For more information on the trials with H11 steel, the reader is referred to the report 'AM of Aluminium Extrusion moulds using H11 steel'.

How important is the anisotropy of the 17-4PH material, and does it change after HT?

Literature indicates that vertically build samples have a lower strengths and elongation as compare to horizontally build samples. The experimental results from samples collected in the current study do not fully support this view. The yield strength of as-build samples is somewhat lower in the vertical direction (-65MPa), but the tensile strength is higher (+85MPa), as well as the elongation (+3%) and reduction in area (+25%). Overall, the difference in properties between the X and Y directions is negligible.

The Directional dependence is removed as a result of HT including solution annealing. The origin for this could be the loss of directionality in the microstructure which has been observed. Samples that did not undergo a solution heat treatment maintain a directional microstructure. However, the directional dependence of this material has not been investigated by means of tensile test specimens. It is therefore not certain that the directionality of the microstructure is the reason for the observed anisotropy. It is also possible that the precipitation of nanosized particles, responsible for strengthening, removes the directional dependence.

Does performing a solution annealing treatment influence the properties of 17-4PH after HT?

Samples that did not undergo a solution annealing heat treatment have a higher hardness, irrespective of the used process parameters. However, samples that were solution annealed have improved tensile

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[6] https://www.sirris.be/inside-metal-additive-manufacturing

properties. While the non-solution annealed samples have a microstructure that is virtually unchanged from the as-build state, the solution annealed samples exhibit a more uniform structure of tempered martensite, with much smaller grain sizes. The tensile test results also indicate that the solution annealed samples have a somewhat higher ductility (elongation 7.5% vs. 4%). A limited amount of necking can be seen on the solution annealed samples, while the non-solution annealed samples appear to have a completely brittle fracture surface. Based on these observations, it may be deduced that omitting solution annealing increases the potential for hardening by precipitation of nanoparticles to some extent, but results in a more brittle material with reduced tensile properties.

How do the properties after HT compare to as-build and conventional material?

The observed spread in as-build properties does not change significantly as a result of HT. However, after solution annealing and H1150 treatment, the tensile strength and elongation spread is reduced. Highest strength and lowest elongation is obtained from a H900 heat treatment. The H1150 treated material has a lower yield strength than the as-built material, but exhibits significant strain hardening in the first 1.5-2% strain after yielding. The tensile strength of the H1150 material exceeds that of the as-built material, but stays well below that of the H900 material. Within the current study, it seems that the AB condition has slightly better properties as compared to the H1150 condition. Compared to the conventional material, the 3D printed material has a lower yield strength (-100MPa) and lower tensile strength (-100MPa) for the H900 treatment. After the H1150 treatment, the yield strength is also significantly lower (-200MPa), but the tensile strength is as expected.

Does a change in process parameters from high power and scan speed to low power and scan speed influence the properties?

Machined as-build (no heat treatment) 17-4PH samples produced with lower power settings have a lower hardness, slightly higher yield strength, lower tensile strength and significantly reduced elongation as compared to those produced with high power settings (same material density). It is therefore clear that there is a (slight) influence of print parameters on the as-build mechanical properties of the 17-4PH steel. However, the results of the heat treatments also indicate that the mechanical properties greatly depend on the applied heat treatment (independent of the chosen print parameters). It appears that the heat treatment has the major effect and overshadows the effect from the change in process parameters.

It can therefore be concluded that for heat-treatable materials like 17-4PH, print process optimisation should focus on optimizing the material density and build speed. The mechanical properties can be optimised by a careful control of the post-build heat treatment. The situation will be different for steels like 316L, where the as-build properties are desired (and often better than the conventional properties). In that case process optimisation should also focus on the mechanical properties.

Does the hardness correlate well to the tensile properties? And can it thus be used as a simple and fast tool for parameter optimization?

The hardness of non-solution annealed samples is higher as compared to solution annealed samples, while the tensile properties are significantly lower. On the other hand, the hardness correlated to the density within a set of similar samples (at low densities <99.2%). It can be concluded that the hardness can be used as an indicator for density, within a set of samples having received the same post treatment and build with similar print parameters. But that it cannot be used as an indicator for the tensile properties when comparing different types of heat treatment and process parameters. This illustrates that hardness measurement is perhaps not the perfect tool for parameter optimisation. It is correlated to density, but density is also quick to measure. In addition, the hardness is only lightly correlated to the process parameters. More importantly, for most applications the tensile properties are the critical parameters, and the hardness does not show a good correlation to the tensile properties.

Does the surface condition influence the tensile properties of 17-4PH steel?

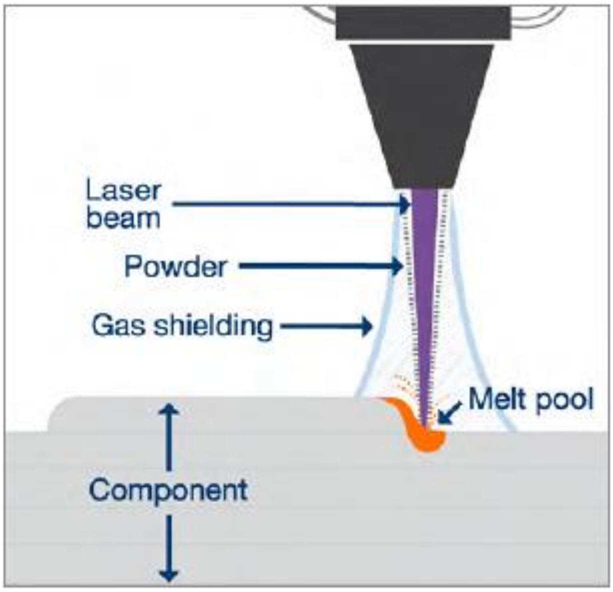
The surface roughness of Near Net Shape parts has a negative impact on the performance of high strength/low elongation materials like the H900 precipitation hardened 17-4PH steel. The more brittle nature of this material results in early fracture resulting from stress concentrators on a rough surface. The impact on materials allowing a larger amount of plastic deformation such as the as-build samples is smaller, however the yield strength is still reduced significantly. Post-processing of the surface to reduce the roughness is advised. As a minimum precaution, cleaning by sand-blasting is suggested, although in the current investigation the effects of sand blasting have not been investigated.

5 LMD and heat treatment of 17-4PH and 316L steel

General

LMD is a Directed Energy Deposition method based on a laser beam that produces a meltpool on the component and into which a metal powder is projected. A 3D geometry is thereby manufactured in a near-net shape approach by depositing consecutive layers of material, consisting of well-defined 2D trajectories, onto each other. Typical deposition speeds of 0.1-1.5 kg/h are obtained when building medium sized parts (typical tolerance ≈ 0.1-0.15mm and surface roughness Ra 20-50µm). The machine is either CNC based or robot based.

Within the project a multi kW diode laser source with ≈ 4.5 mm focal spot was used. This LMD head is integrated on a 6-axis robot equipped with an additional external axes.



Source : Lloyd's Register & TWI Ltd

The Q&A mentioned below are an overview of the lessons learned within the project. More in-depth information can be found in the document 'LMD processing and testing' on the project webpage[7].

How are process parameters typically selected?

The approach for LMD is similar to SLM i.e. first a parameter screening for appropriate sample density (e.g. 99.95%) a then for speed/stability (control of heat input)

If no previously determined parameters can be re-used, than the deposition of a series of simple geometries will be performed. Single track walls of 10-20 layers based, on different parameter combinations, can be used to get a first idea of a stable parameter window with a new material on a specific LMD machine. In the case of LMD processing the deposit width mainly depends on the size of the laser focal spot and it changes only a little bit with varying process parameters. This basically means that part wall thicknesses will be produced as a multiple of the focal spot size.

Within this coarse parameter window, different parameter screening tests will be performed by depositing volume elements of e.g. 20x20x10mm with potentially interesting overlap %, different layer strategies etc. In this phase typically following parameters are combined at 2 or 3 different levels:

- laser power (kW)
- travel speed (mm/min)
- powder flow (cc/min)

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[7] https://www.sirris.be/inside-metal-additive-manufacturing

- Argon shielding gas flow (l/min)

After all these volume elements have been produced, they are sectioned for metallographic inspection to demonstrate sound deposits i.e. limited porosity and good adhesion between tracks. Out of these best deposits parameters combinations can be selected for either highest quality, high deposition rate at acceptable quality, lowest heat input etc.

Is there a faster parameter screening approach possible when less optimization is required?

A faster parameter screening method that works quite well in most cases, e.g. when there is already experience obtained with a similar material, is the following:
(1) Set an average power & flow rate, change the travel speed for modifying layer height (*)
(2) Repeat (*) for various power/flow rate combinations in order to better describe the available processing window (stability & porosity) while taking into account that
- the track width (deposit) is mainly defined by the focal spot size
- typically a 30% overlap is used for multi-pass deposits
- optimized paths & improved heat input control might be required for certain geometries

During deposition of prototype parts travel speeds of 0.75-1.0m/min for bead widths of 3.8mm and deposition rates of 0.7-0.9kg/h have proven to be stable parameter settings. For straight walls of 17-4PH steel a surface roughness of Ra ≈ 25µm obtained, this mainly due to the waviness between deposits (even for straight walls). Using a 1-2min between layers for avoiding overheating and changing the start and stop position between layers are also important aspects.

What to do when the part geometry that is to be manufactured has inclined walls or free hanging sections ?

Currently LMD is performed without any support structures put in place, hence manufacturing of free hanging sections as such is not really possible. Since LMD can also be used to build onto existing surfaces it is sometimes possible to reposition the part various times and start building each time in another direction. That way e.g. a T geometry can be produced by first building the vertical wall and then repositioning the part on its side. Inclined walls can be deposited but the max. overhang angle will depend on the process parameters, cross-section geometry etc. During hollow dome deposition (i.e. consecutive circular tracks of decreasing diameter onto each other) tests it was possible to successfully build until a 15° inclination, this with the LMD head positioned along the Z-axis. Additionally, the LMD head position can be optimized to increase this angle i.e. when using a 6-axis robot it is beneficial to position the head along the surface tangent instead of merely along the vertical Z-axis.

Is it possible to produce hollow parts with internal reinforcements by LMD?

Indeed, within the framework of the project several parts with simple lattice structures have been printed. These structures are typically no full 3D geometry, as is the case for SLM parts, but rather 2.5D geometry (i.e. extruded patterns). Although specific software might enable the trajectory generation for more complex internal structures, the LMD process will not be able to build as fine and complex as the SLM process (e.g. more intricate gradient or honeycomb structures). This due to wider deposition tracks, potential loss of processing stability (e.g. too many hot spots at sharp corners) and the incapability of crossing trajectories (since this would lead to local over thickness).

What about the mechanical characteristics of parts obtained with LMD?

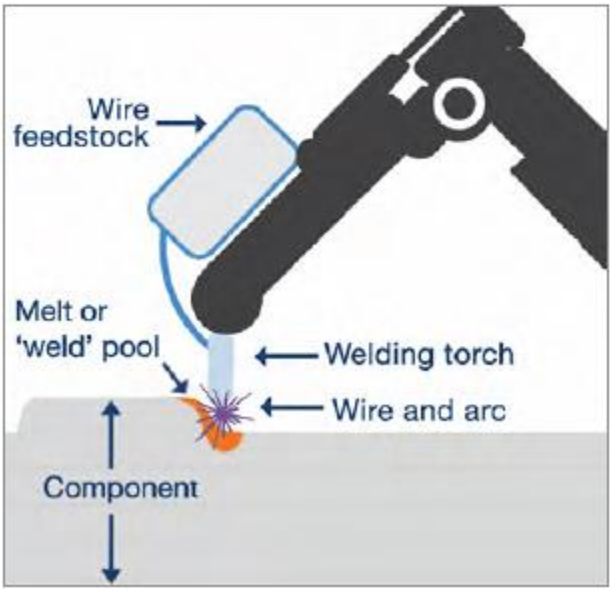
Hereunder an overview of the obtained mechanical characteristics for WAAM vs LMD 316L deposits and SLM vs LMD 17-4PH deposits (after H900 heat treatment). All mechanical testing was performed at room temperature (22°C).

	Hardness HV	Yield strength (MPa)	Tensile strength (MPa)	Elongation (%)	Charpy (section) (J)
WAAM 316LSi Horizontal dir.	200	376	580	36	108.6 (10x10mm)
WAAM 316LSi Vertical dir.	/	368	625	37	130.5 (5x10mm)
LMD 316L Horizontal dir.	190	360	590	32	38 (5x10mm)
LMD 316L Vertical dir.	/	330	550	35	48 (5x10mm)
SLM 17-4PH Horizontal dir. H900 treatment	425	780	900	13	
SLM 17-4PH Vertical dir. H900 treatment	/	730	990	16	
LMD 17-4PH Horizontal dir. H900 treatment	450	1080	1470	13.5	2.2 (2.5x10mm)
LMD 17-4PH Vertical dir. H900 treatment	/	1000	1220	11.5	3 (2.5x10mm)

In general the values for WAAM vs LMD are similar but for WAAM samples the difference between vertical and horizontal direction seems to be less clear. For the 17-4PH material the difference of SLM vs LMD seems to be more important. This probably also because the SLM parts have first undergone a solution annealing step.

6 WAAM and heat treatment of 2209 and S355 steel

WAAM is a Directed Energy Deposition method based on an electric arc that produces a melt pool on the component and into which a metal wire is deposited. A 3D geometry is thereby manufactured in a near-net shape approach by depositing consecutive layers of material, consisting of well-defined 2D trajectories, onto each other. Typical deposition speeds of 0.5-4 kg/h are obtained when building medium and large sized parts (typical tolerances ≥ 0.2mm and surface roughness of Ra 500µm incl. important waviness). The machine is either CNC based or robot based. Methods based on a non-consumable electrode (GTAW and plasma processes) will typically generate more precise contours and higher quality deposits (most used for Ti alloys, specific Al alloys etc.). Methods based on consumable electrode (GMAW i.e. filler wire being molten and projected into the melt pool) will typically generate higher deposition speeds and are easier to implement.



Source : Lloyd's Register & TWI Ltd

Within the project a GMAW source with synergic curves, capable of depositing 0.8mm up to 1.6mm filler wire was used (wire diam. 1.2mm was used for nearly all tests). The welding torch has been combined with a 6-axis robot and an additional rotating table.

The Q&A mentioned below are an overview of the lessons learned within the project. More in-depth information can be found in the document 'WAAM processing and testing' on the project webpage[8].

What are important parameters for the WAAM processing?
The most important process parameters are the welding speed (TS) and the wire feed speed (WFS). When using a welding source with synergic curves the current and voltage are automatically coupled with the WFS. Using wire of diam. 1.2mm and wire speeds of 2 to 8m/min, combined with 0.5-0.6m/min welding speed, typical deposit widths of 2.5 to 7mm (single pass and without weaving) and bead heights of 1.5 to 3mm can be obtained.
Welding with a longer arc sometimes leads to reduced projections but a shorter arc is more stable. Also, it has been shown that arc lengths of > 15mm lead to increased porosity in the deposit. In some cases the use of a specific shielding gas might be appropriate (e.g. some additional He leads to a "hotter" arc and typically a smoother surface). It is however good practice to foresee +/- 2mm surplus material on 3D geometry so that after machining the required dimensions and surface roughness are obtained. It is therefore typically not useful to optimize the surface waviness.
Typically walls as thin as 1.5-2mm should be possible to manufacture with the appropriate wire and process parameters. It should be mentioned that these walls will often not have an evenly distributed thickness since there will be bumps etc. on the surface.

How to select process parameters for WAAM?
(1) Select a wire diameter for the desired wall thickness and productivity (kg/h).
(2) The welding speed, TS, will be generally limited to ≈ 0.6m/min in order to avoid "humping" phenomenon (melt pool instability).
(3) First a number of screening tests are performed to define WFS/TS ratios that work well. Once these are defined, the most appropriate WFS/TS ratio will be respected for approximately constant heat input for a series of different deposit widths and heights.
(4) Different synergic curves typically lead to a different heat input (for the same wire speed). This might not only have an influence on the bead width and height but also on the processability and final microstructure. It seems that a pulsed process yields a good results for many materials, thus probably due to the improved control of the heat input.
Typically, the first layer(s) will be applied with somewhat higher heat input or with pre-heated substrate in order to assure sufficient weld penetration to the substrate. In some cases, e.g. sensitive material microstructures, the bottom and top 3 to 5 layers are considered of lesser quality because the process conditions are not deemed stable.

How much time is required to enable cooling down of the workpiece between passes?
A wait time is often programmed between subsequent passes or layers (depending on the number of passes per layer and the heat input) in order to avoid material overheating. On materials with a high sensitivity to interpass temperatures (e.g. < 150°C required for duplex steels) it might be more suitable to program a wait time after each pass. On less sensitive materials such as structural steel etc. this could be done after each layer. When using a 2-10min. cooldown (depending on the wall thickness) this might lead to continuous temperatures of +/- 300°C on thick parts. Unfortunately, the cooling time required to reach the interpass temperature can easily lead to idle time that can represent more than 30% of the total printing.

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[8] https://www.sirris.be/inside-metal-additive-manufacturing

It would therefore be beneficial to include some optimized temperature control (e.g. forced cooling where acceptable) or process control (e.g. wait time or parameter variation based on measured temperatures).

What to do when the part geometry has inclined walls or free hanging sections?
Currently WAAM is performed without any support structures put in place, hence manufacturing of free hanging sections as such is not really possible. In some cases it is possible to position or divide the 3D part in different sections than can be welded together afterwards. Inclined wall can be deposited but the max. overhang angle will depend e.g. on the materials (melt pool fluidity), the process parameters (melt pool size) etc. During testing walls with a 15° inclination (from vertical) have been deposited just with the torch positioned along the Z-axis. Additionally, the torch position can be optimized to increase this angle i.e. when using a 6-axis robot it is beneficial to position the torch along the surface tangent instead of merely along the vertical Z-axis.

What else besides a high quality welding wire and synergic GMAW source would you need to perform WAAM?
One of the most important features a WAAM machine should include is a software for the generation of appropriate trajectories and ideally some feedback loop regarding the actual distance between contact tip and workpiece.
In general the following information and processing is to be handled by the software:
(1) different WAAM parameters e.g. welding speed, welding job (current, voltage) at different positions for optimal processing (hotter and colder regions due to wall thickness variations, colder deposits at the outer edges and hotter filling parameters etc.).
(2) pass overlap schedule i.e. the typical displacement between 2 passes deposited side by side should be about 65-75% of the bead width. All trajectories generated by the software should take this into account since else arc instability might occur.
(3) in/out trajectory sequence optimization i.e. subsequent weld starts & stops should not be repeated at the same position for consecutive passes and typically a 5-10mm overlap (with ramp up/down) is applied.
Especially (2) and (3) are rarely handled correctly by a standard (slicer) software thereby requiring quite some manual modifications. WAAM processing is therefore known to require a software that leaves sufficient possibilities for the user to optimize trajectory generation etc.
Additionally the contact tip wear and tear should be monitored (either by direct or indirect inspection) because of its important role in the process. When using hard wires, with extreme but acceptable helix and cast, they cause a lot of abrasion. For that reason the central hole in the tip becomes too large or becomes oval thereby leading to an unstable arc. Changing the contact tip every couple of hours with intense WAAM processing will become necessary.

What about the composition of the filler wire vs deposit after WAAM?
Just as in the case of welding there might be a loss of certain elements due to the electric arc. Since WAAM is often performed at limited currents this effect is rather low. The opposite is also true, e.g. when processing stainless steels with an Ar + 2.5%CO_2 gas it has been demonstrated that a carbon pick-up of 0.01-0.015% is also possible. In either case, element % variations due to WAAM are typically too low to be relevant.

What mechanical characteristics can be expected of WAAM structures?
During the project a lot of different wall thicknesses have been produced with various processing parameters for samples in S355, 316L and 2209 duplex steel.
On WAAM samples produced with welding wire for S355 steel (i.e. ≈ equivalent to S420 steel) the yield and tensile strength are often 10% better than expected (≈ 480MPa and ≈ 600MPa) also at somewhat

higher interpass temperatures e.g. 200°C. Even elongations of > 30% and very good Charpy values have been obtained with little difference in horizontal and vertical direction.

On WAAM samples produced with S316LSi welding wire a similar behavior was obtained as with S355 wire. Values were again ≈ 10% better than expected, again with little difference between the horizontal and vertical direction (somewhat higher tensile strength and Charpy values in vertical direction).

On WAAM samples produced with 2209 duplex steel welding wire the yield and tensile strength were 20% better than expected. Although the Charpy values were more than sufficient, the elongation was just enough. Also the difference between the values obtained on horizontal vs vertical samples was more pronounced. It has to be said that on this material the max. interpass temperature of 150°C was sometimes exceeded.

7 Surface post-processing of 3D printed steel parts

A whole series of potential postprocessing technologies are available but sometimes lesser known, too expensive (except for high value added parts from medical, aerospace, …), etc. Some of them are well known because they have been used since the beginning of metal AM processing and/or because they have been copied from other industries or applications (e.g. chemical and electrolytic polishing is also used in the chemical and pharmaceutical industry). They can be based on a single process such as grinding for the removal of the supports, chemical polishing for reducing the surface roughness etc. In other cases, e.g. for certain commercial systems like Hirtisation by Hirtenberger, a combination of different technologies will consecutively remove supports and provide coarse and fine surface roughness optimization.

The following surface postprocessing is typically to be performed in SLM metal AM:

- removal of partially melted grains and powder cake
- removal of support structures (often after some kind of heat treatment)
- decrease/optimization of the surface roughness

In case of LMD and WAAM, support structures will not have to be removed (since they are not present in the process). The surface topology will also be quite different from SLM parts because the surface waviness and staircasing effect are more important (especially for WAAM).

Hereby an overview of the best known technologies for post-processing metal AM parts:

- grinding, cutting, EDM (typically for removing parts from build plate & support removal)
- machining (e.g. mating surfaces in assemblies etc.)
- sandblasting (SB)
- tribofinishing (TF), without or with active component i.e. typically acid solution (Remchem)
- chemical polishing (CP)
- electrolytic polishing (EP) / wet or dry method (no liquid electrolyte)

Hereby an overview of some well-known commercial and/or patented technologies:

- Plasotec, electrolytic plasma polishing (pulsed)
- Hirtenberger – Hirtisation, combination of electrochemical pulse methods, hydrodynamic flow and particle assisted chemical removal
- Extrude Hone – Abrasive Flow Machining, abrasive paste that polishes the surface while flowing along it (potentially important tooling cost)
- Extrude Hone – CoolPulse, optimized electrochemical polishing method (potentially important cathode cost)
- Best In Class – Micro Machining Process, little was made public regarding the process
- DLite – DryLite, dry particle electropolishing

In the INSIDE Metal AM project, samples have been mainly postprocessed by tribofinishing, chemical polishing and electrolytic polishing. Since LMD samples have a more pronounced surface waviness than SLM parts (depending on the applied layer height), processing typically takes longer. In order to verify a potential acceleration of the postprocessing, the combination of different methods has also been tested. Most postprocessing methods suitable for SLM parts are not appropriate for WAAM parts, even though the process parameters and shielding gas can be optimized for reducing the surface roughness (e.g. selection of shielding gas that incl. He). In addition, the As Built part dimensions are rarely within the required final tolerance. Therefore typically excess material is applied so that relevant surfaces for assembly, fatigue resistance etc. are simply machined to the desired dimensions and required roughness.

The Q&A mentioned below are an overview of the lessons learned within the project. More in-depth information can be found in the document 'Surface finishing of SLM and LMD prints' on the project webpage[9]*.*

What about the final surface roughness to be obtained on a certain AM part?

The technical part specifications will also mention the roughness to be obtained (in general or on certain surfaces) after postprocessing. There is no general value that is to be used since this will depend on the final application. It is important to consider which components of the roughness profile need to be removed and for what reason. Surfaces that are used to control a gas flow will probably require a different final roughness than parts for general mechanical assembly (e.g. Airbus AIPS 01-04-020 high quality requires Ra ≤ 3.2µm). When looking at the surface roughness in detail it should therefore be mentioned that not only the Ra (Rz) value is to be considered for a certain application but also the skewness (Rsk) plays an important role. This parameter gives an indication for the amount of peaks vs valleys on the surface. It will therefore also be a measure for the required postprocessing effort since peaks and valleys are not removed with the same ease (peaks are typically removed easier).

Can chemical or electrolytic polishing be applied on the As Built part?

Sandblasting, or a similar technique, should be applied to SLM and LMD parts before polishing. SLM parts will typically have unmolten particles stuck on the surface that will require additional polishing time if they are not removed. LMD part surfaces are potentially covered with oxides due to the ambient air (vs SLM that is performed in Ar environment), this oxide film is to be removed for polishing homogeneity. It has the additional advantage of also reducing the initial roughness by removing peaks e.g. LMD 17-4PH part with Ra 20-25µm in As Built condition but already reduced to 14µm after sand blasting.

Do tribofinishing, chemical polishing and electrolytic finishing arrive to similar results on SLM and LMD parts ?

In general a similar result can be obtained on SLM and LMD produced parts, as was tested within the project, but no necessarily with the same durations. Although, in some cases what works well on SLM parts doesn't seem to be compatible with LDM parts.

Tribofinishing conditions can be transferred from SLM to LMD parts but longer treatment times are required. After 5h an Ra ≈ 6µm is obtained and saturation of the roughness value (Ra ≈ 3µm) is observed after 20h. Since the abrasive particles preferentially remove peaks, the waviness is efficiently removed without impacting the final dimensions. A dull-grey surface finish is present after postprocessing. Surprisingly the H900 heat treatment (reduced hardness compared to As Built) doesn't seem to make a relevant difference.

Chemical polishing on LMD surfaces was performed by using an electrolyte previously validated on 316L SLM samples. However, on 316L and 17-4PH LMD samples only limited surface smoothing as observed. After some additional trials it has been shown that chemical polishing, at least using a typical electrolyte, doesn't seem to be efficient on LMD samples

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[9] https://www.sirris.be/inside-metal-additive-manufacturing

Electrolytic polishing (i.e. controlled accelerated corrosion) has been tested for reference on SLM parts with 2 different electrolyte. The 1st electrolyte (mineral acid mix initially developed for stainless steel) didn't perform well at any current density and is therefore considered inefficient for this purpose. The 2nd electrolyte (organic acid mix initially performed for tool steel) works a lot better and surface roughness of Ra ≈ 4µm is obtained after 1.5h. The peaks in the surface profile are well removed but the general waviness is a lot harder to remove. The processing conditions can be transferred to LMD parts but due to the higher waviness longer processing is required (e.g. after 1h an Ra ≈ 6µm is obtained on SLM parts while on LMD this takes 2.5h). The behaviour on 316L and 17-4PH materials seems to be similar and H900 heat treatment doesn't seem to make a difference. However, once most of the peaks are removed the electrolytic polishing starts to attack the entire surface profile leading to more material removal.

Can it be beneficial to combine postprocessing methods on LMD parts in order to reduce the surface roughness faster?

Indeed, tests have been performed with several combinations, the most interesting being:

1. sandblasting + tribofinishing (8h) + electrolytic polishing (0.5h)
2. sandblasting + electrolytic polishing (3h) + tribofinishing (2h)

In both cases the required 16-20h of only tribofinishing in order to obtain a surface finish of Ra ≈ 4µm can be reduced by 50-75% by combining both methods. When using combination (2) the tribofinishing leads to a dull grey surface, this can be easily removed by 0.25h additional electrolytic polishing. Also the longer electrolytic polishing will remove somewhat more material so that dimensional tolerances should be verified.

What about the cost of surface postprocessing of SLM and LMD parts?

It is nearly impossible to give a general indication of the cost for postprocessing a part since too many aspects play a role:

- material family (Ti alloys, steels, …), part size, initial surface roughness and supports, etc.
- applied technology, required specific tooling cost, batch size, automation degree, etc.
- special measures to be taken (e.g. avoid unwanted removal of sharp or small features)

With some technologies and part geometries surface roughness values of e.g. 2µm will be hardly achievable, or only after many hours of postprocessing, making them of little practical use. In order to have some idea of the cost a quotation was asked for post processing a metal part of medium size (e.g. 150x75x75mm). Prices of 500-3000€ were obtained for processing a single prototype part, these were however reduced to 15-20% for larger batch sizes.

How to select the best method for surface postprocessing of SLM parts?

Here again, as mentioned regarding the cost, a lot of very different aspects might drive the selection of a certain technology. An overview table, giving a first indication can be found in the document 'Surface finishing of SLM and LMD prints' on the project webpage.

8 Demonstrators - Comparison of conventional vs AM approach

A direct cost comparison of conventional production methods (machining, bending, welding, casting or a combination of techniques) compared to Additive Manufacturing could be carried out in terms of machine, labour, material and energy costs. However, carrying out these types of comparisons can depend a lot on the individual component and on the different assumptions set, therefore here no cost calculations will be proposed, but based on the experience from the different demonstrators studied in the project some main lessons learned will be shared. Moreover, it is not correct to make a direct comparison of the cost of the part itself, since the added value of Additive Manufacturing is often found elsewhere, like weight reductions or improved process efficiencies (e.g. cooling channels in moulds), of which the gain can far outweigh an increase in part cost.

It should be remarked that the costs for qualification and quality control are often omitted in an economic evaluation, even though this can be a significant factor. Recently more guidelines are being developed that define ways of approving materials, products and/or components for AM. These specifications aim to provide confidence to the end users of the AM products. However, often the actual testing within these procedures can be more extensive than for conventional processing. Partly this is related to the AM products: these can have anisotropy in mechanical properties over the different orientations or layers, or mechanical properties that are heavily dependent on the actual parameters that were used during the build, and partly make up for the fact that less statistical (historical) information is available for similar products/production techniques. For companies interested in using AM metal products, it is very important to define the qualification, testing procedures and acceptance criteria for their application, to avoid unforeseen costs in the qualification of machine, powder/wire, process parameters, test builds and/or final product testing. The level of qualification and certification required will strongly depend on the criticality and safety concerns related to the part.

L-PBF, example of 3D printed inserts for extrusion dies

Conventional aluminium extrusion moulds are manufactured from H11 or H13 steel that is often nitride to increase the surface hardness. In a four cavity die (which can extrude 4 profiles simultaneously), one of the cavities typically fails first. When this happens, the entire die needs to be replaced. If 3D printed, replaceable inserts would be used, this could potentially reduce the down-time and save the die. It was decided to first test the performance of the 3D printed material, in this case H11 steel, by printing a simple ring that is part of a mould assembly. H11 steel requires specific machines that can preheat the powder bed to 500°C. The test ring was thus printed in collaboration with VAC Machines in Bruges and Trumpf. The ring has an outer diameter of 78mm and a height of 10mm. The 3D printed part turned out to have a good hardness, fine cellular microstructure and minimal porosity. It performed exceptionally well and was at the time of writing or this report still being used in production. Unfortunately the tight tolerances on the extrusion channel require that post-machining of the printed part is required, thereby losing the major advantages AM could offer here. As a result, 3D printing of inserts was abandoned. However, the excellent performance of the test ring opened up a new opportunity: printing of conformal cooling channels around the die could help improve the process stability for extrusion with recycled aluminium, something which has not yet been considered in this industry.

This illustrates that innovation does not always need to follow a predefined trajectory and creativity is key. This specific demonstration example, although not leading up to what we had initially expected, led to three important outcomes: (1) know-how on printing of H11, (2) the idea for cost reduction by using interchangeable inserts was discovered and remains valid, albeit with conventionally manufactured inserts and (3) use of conformal cooling as a new innovation idea for aluminium extrusion (with a sustainable touch).

A rough figure of about €70/hour machine time was used for the cost estimation of the printed inserts, but redesign of the part, handling/setting up costs and in this case post machining significantly impact the total cost, which was not calculated in detail. Although it was quickly established that the inserts would be too expensive when manufactured via L-PBF, the idea of cost reduction by using replaceable inserts was maintained, albeit manufactured conventionally. As indicated above, the investigation did not stop there, as clearly cost per part will in most cases not be the reason to AM. In this case, L-PBF can really show its advantages not so much in the cost per part, but in the added functionalities, or added value overall, like:

- Printing cooling/heating channels directly in the part (preheating of the die before use, and cooling during use will increase the lifetime of the part significantly)
- Provide lubricant channels (also resulting in a longer lifetime of the part)
- Combining several parts into one

More information on the results of this case study, can be found in the document 'AM of Aluminium Extrusion moulds using H11 steel' on the project webpage[10].

General rotor, produced by two different techniques: LMD and L-PBF

This demonstrator was designed as a showcase to compare the possibilities of two AM techniques: LMD and L-PBF. A summary of the comparison is given here. *More information on this demonstrator and the comparison between the two techniques can be found in the document 'L-PBF vs. LMD - Case study using a Generalised Rotor' on the project webpage*[10].

A direct cost comparison between the LMD and L-PBF part is possible, but depends on a lot of boundary conditions (the required tolerances, the required surface finish, machine settings, etc.). Moreover, as was the case for the extrusion moulds, the real added value can come not from part cost, but by adding functionality (e.g. cooling channels, lubrication channels, weight/inertia reduction) or in spare part management (no stock of spare parts/moulds required). The total cost of machine time and powder was estimated to be in the range of 1100-2150 euro for the L-PBF part and 1000-1600 euro for the LMD part. The large range illustrates the dependence on process settings. Finishing of the rotors is not included in this cost.

As mentioned, a direct cost comparison is not a fair comparison of both technologies. Other aspects, like the ability to generate intricate shapes or the required wall thickness also need to be taken into account. A more intricate internal lattice structure could be made by L-PBF, with even a gradient within this structure, LMD is a bit more limited in geometry, but also here a hollow rotor with internal lattices could be achieved. The LMD part on the other hand is much faster to print and can more easily be made more robust (larger wall thicknesses).

A complex shaped, cast rotor (not including machining) would typically cost around 100 euro. However, as mentioned before, only comparing the part cost is not relevant. Large benefits during the service life could for example be foreseen in terms of thermal management. These types of parts are often cooled from the outside, where the AM (LMD or L-PFB) produced parts would allow direct internal cooling, with possible added benefits that far outweigh any cost increase of the part.

The core message here is, that exploring the use of AM should be seen as an opportunity to look for the advantages and added value AM can bring. This will require re-thinking and re-engineering existing parts and processes. The possible gains can be significant, but will also require creativity in product design (application engineers), an investment to acquire the necessary insights and expertise (possibly using external support) and an investment to re-shape existing products and services.

Cast part, replaced by WAAM produced part

The demonstrator produced by WAAM was designed to be able to investigate the use of AM for producing large spare parts. Here the reason for moving to AM is not related to a cost comparison, but due to the fact that for these (mostly cast) parts, the delivery terms can be very long, and part obsolescence plays a key role. In terms of qualification costs, it is expected that these costs should be lower for the WAAM process, as the material feedstock is based on wire materials commercially available for conventional welding. The actual cost of having to replace a large (worn/broken) part, can be substantial though, especially if there is no casting mould available any more, in such cases the conventional casting would include (designing) and making of the mould, and of course casting for very small quantities, in specific alloy composition also entails a large cost.

WAAM products normally require various post-processing steps, including machining, where the choice between a WAAM part with dimensions close to the final shape (requiring less machining) or a cheaper produced WAAM part (with more machining) would have to be part of the actual cost calculation, from the design stage.

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[10] https://www.sirris.be/inside-metal-additive-manufacturing

Main lessons learned with regards to economical comparison AM versus conventional produced parts

- For most metal structural parts, the AM production method is still a more expensive method.
- There are large differences between the various AM production methods for metal structural parts, making it difficult to carry out a one-on-one cost comparison calculation.
- In most cases, where the conventional versus an AM production method is foreseen for metal structural parts, cost is not the driver.
- Exploring the use of AM should be seen as an opportunity to add value to existing products and services, and requires creativity in re-shaping products and services.

9 Concluding Remarks

When embarking on a journey towards the implementation of metal 3D printed parts, there are a lot of decisions to be made and questions answered. Luckily, you are not on your own when it comes to finding answers. Experience and expertise is available both from funded projects like the INSIDE Metal AM projects and commercial service providers. The answers given in this white paper are only a first introduction. The best way forward is to talk to technology experts about your doubts, ideas and the opportunities and challenges that you see.

Everybody has to make this journey at their own speed. For many companies it can be interesting to start small, others will want to define a clear roadmap, set goals and set aside investment budgets in order to move faster. In all cases, it’s a good idea to follow an introductory training and talk to experts. But in order to actually put what you have learned in practice, it is also important to get comfortable with the technology and the material performance. For that you need to take to step to actually printing a part. To keep the initial costs low, it is often interesting to start with a small, non-critical part (that doesn’t need certification). A product/component scan could be performed to see where AM can bring the highest added value. Next, you might decide to also get some experience with minor re-engineering to make use of the advantages AM offers. A part can then be printed at an external service provider. The first part will likely not yet be optimal and the business case not yet entirely sound, if you think it is, something probably got overlooked. However, if you never take the first step, you also can’t take the next steps to fully realising the potential of AM.

As a final remark, it can be pointed out that, depending on your company size and what you want to do, funding can often be found for the type of innovation trajectory that is required to successfully implement AM. At Sirris, CRM and BIL, we are always available to talk with you about the many possibilities that AM offers and what could be the best way for you to realise them.

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