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The Metal Additive Manufacturing Journey For Industry

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The Metal Additive Manufacturing Journey For Industry

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Contents

Foreword

The tooling industry is characterized by low production volumes, a very specific knowledge field, and a demand for highly experienced manpower. That is the picture of a suitable match to the offers and requirements from the wide range of techniques classified as additive manufacturing. The described scenario portrayed the origins of "Project FERA", as a framework for the dissemination of metallic additive manufacturing technologies within the Brazilian tooling industry, through the government program "ROTA 2030".

To effectively achieve the desired dissemination, the group had to be representative of the industry. Encompassing the entire production chain, 26 companies joined 4 research institutes. The several federal units represented were still reinforced by an international presence, as any disruptive initiative must stand for. Among the distinct results of the three first years of cooperation, part of the outcomes is herein registered.

This document is not a book. It does not aim to be a scientific publication. This textbook was conceived to be a first-reading alternative for those who need to decide to invest in additive manufacturing. It was necessary to build a simple and straightforward architecture, to allow breaking a misconceived mindset that additive manufacturing would be excessively complicated for the tooling industry. The same principle that guided the activities of the project FERA.

Some of the herein presented information, indeed, comes from the project. However, they were inserted to demonstrate the theoretical fundamentals of the additive technology. Along the textbook, the reader will find explicit and tacit knowledge about the entire manufacturing journey. It covers contents before and after the layers' deposition, from the powder to the post-processing stages.

On behalf of the entire group, our genuine expectation is that we can motivate more professionals to adopt metallic additive manufacturing transversally to the industry. But we also hope to inspire further fruitful Academia-Industry cooperations such as the project FERA did.

Ronnie Rego, Prof. Dr.
FERA Project Coordinator
Aeronautics Institute of Technology – ITA
Competence Center in Manufacturing – CCM

About FERA

FERA – *"Ferramentas Manufaturadas Aditivamente"* was a project of the ROTA 2030 program in a consortium framework, an initiative of the Brazilian Government to improve the competitivity of the Brazilian industry and the technological content of vehicles, through the dissemination of the additive manufacturing techniques. Between 2020 and 2023, the consortium of FERA was formed by three Brazilian research and development institutes ITA (*Instituto Tecnológico de Aeronáutica*), IPT (*Instituto de Pesquisas Tecnológicas*), and ISI Laser (*Instituto SENAI de Inovação em Laser e Metrologia*), also in a partnership with the German research institute Fraunhofer IPK (*Fraunhofer-Institut für Produktionsanlagen und Konstruktionstechnik*). Together with these four research institutes, 26 Brazilian companies accompanied and guided the development to transfer the technology to the Brazilian industry at the end of the project.

About This Textbook

"The Metal Additive Manufacturing Journey for Industry" is a compilation of the most important developments made within the FERA project in the light of breaking an untouchable feasibility of additive manufacturing. As a mindset changer, it is of great value for the implementation of additive manufacturing applications in the Brazilian industry.

This textbook is organized into five chapters, each focusing on key aspects of Additive Manufacturing (AM). In the first chapter, "How to Apply AM in Industry?", the practical application of AM across various industries is approached, shedding light on its benefits and challenges. Chapter two, "AM Technologies", provides an overall understanding of the diverse AM technologies available, exploring their unique features and specific use cases. The third chapter, "What about materials?", delves into how the characteristics of the raw material can impact the deposition and performance of 3D-printed components. In chapter four, "AM Parametrization: What has to be done before building components", there are discussed the critical parameters that need to be configured before commencing the 3D printing process to ensure quality and precision in the end products. The following session, chapter five, brings an initial presentation of how to post-process the in-built components, with regard to the surface integrity feature that matches its functional requirements. Finally, in chapter six, "Design for Additive Manufacturing", best practices in designing specifically for AM are covered, emphasizing how to create parts that fully harness the benefits of this innovative technology. This chapter structure is designed to serve as a comprehensive guide, offering a practical and in-depth exploration of the world of Additive Manufacturing.

1. How to Apply AM in the Industry?

Eng. Felipe de Sá Carneiro; M.Sc. Bruno Henrique Oliveira de Lima

The successful implementation of bottom-up technology depends directly on the ability of managers to formulate appropriate **strategic guidelines**. Lack of direction in technological investments can lead to poor quality parts, a shortage of qualified personnel, and idle machines. It is therefore important to understand the existing implementation models to select the one that makes the most sense for the case.

Industrial implementation models for additive manufacturing have been gaining notoriety over the last decade, driven by the trends of the Industry 4.0 concept. Mellor(1) presents a conceptual framework in which external forces and internal strategies, divided into **five factors** (Figure 1), guide the definition of the implementation approach. Each internal factor and how it should be analyzed within the industry will be presented.

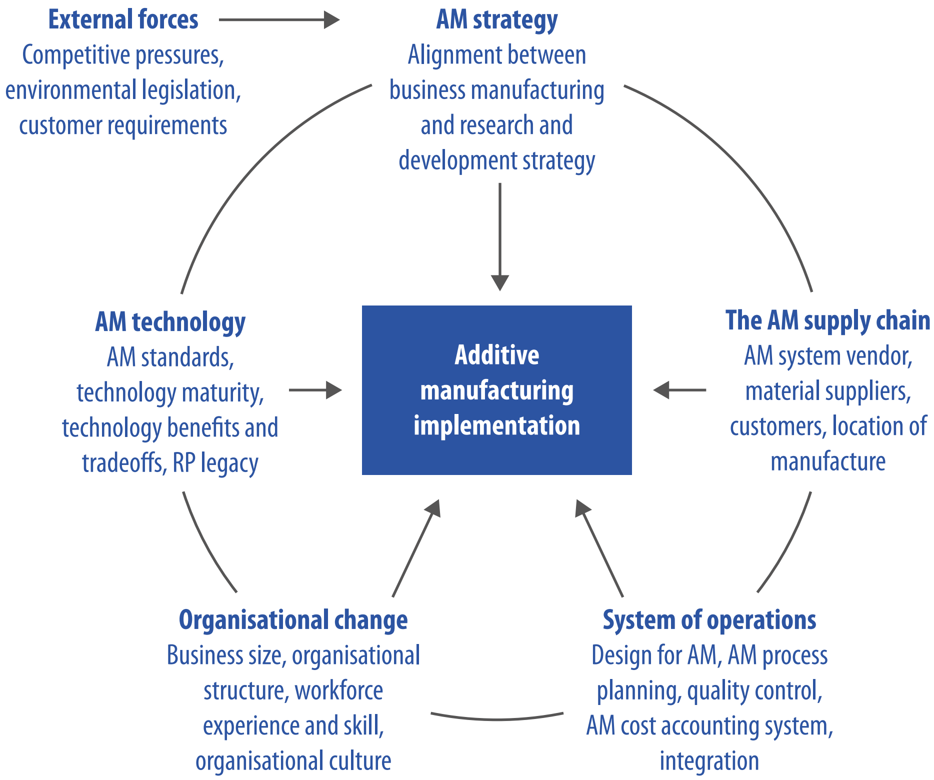


Figure 1. Proposed framework of AM implementation.(1)

1.1. Strategic Factors

As with any major investment, it is necessary to understand the current additive manufacturing market and its players before investing in it. However, market-pull strategies cannot be used alone. Due to the **high degree of complexity and innovation** involved in AM, it demands an alignment between the business, manufacturing, and R&D sectors. In this way, the technical and economic viability of the process is defined for the company's reality.

Strategically, the authors selected **three characteristics** that make products acceptable for AM production: (1) highly customizable products, (2) design-optimized products, and (3) low-volume products. Other strategic applications are the use of this technology for tooling repair or alloy coating (Figure 2).

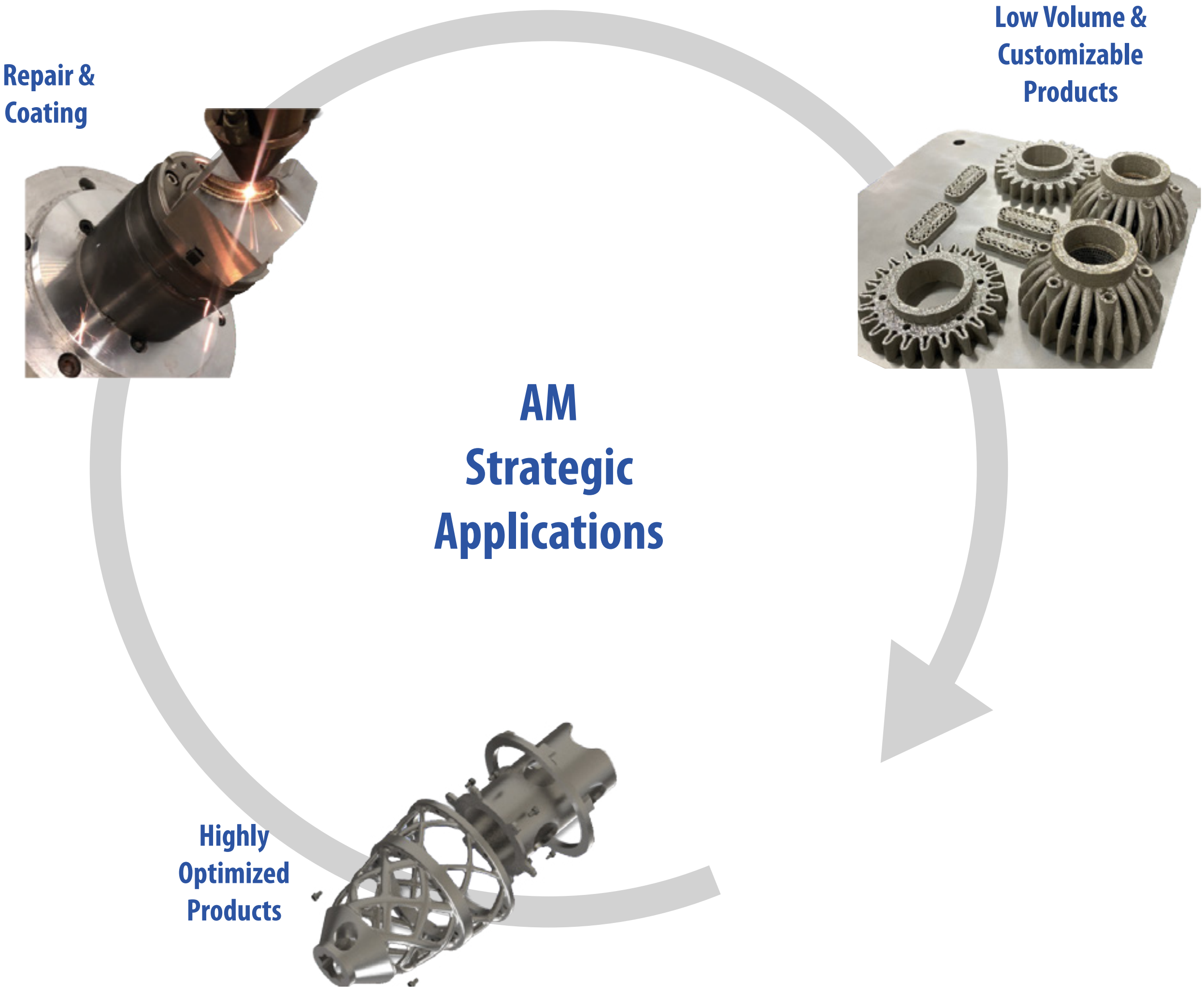


Figure 2. Strategic applications for additive manufacturing in industry.

1.2. Technological Factors

There is a mindset that correlates additive manufacturing with rapid prototyping practices. This correlation, while valid, does not represent the full potential that this technology offers. It is up to the technical sectors to break this paradigm in their companies and present all the existing AM methods internally, as well as their capabilities.

Figure 3 gives an overview of the industrial landscape in terms of the adoption of AM technologies.(2) Powder-bed fusion (PBF) processes are currently more mature and widely adopted by the industry. Even so, such processes have limitations in terms of **materials and setup time**. These limitations do not exist in the same extension for other processes, such as DED (Direct Energy Deposition). It is, therefore, necessary to have a proper understanding of the **trade-offs** that characterize each process before implementing it.

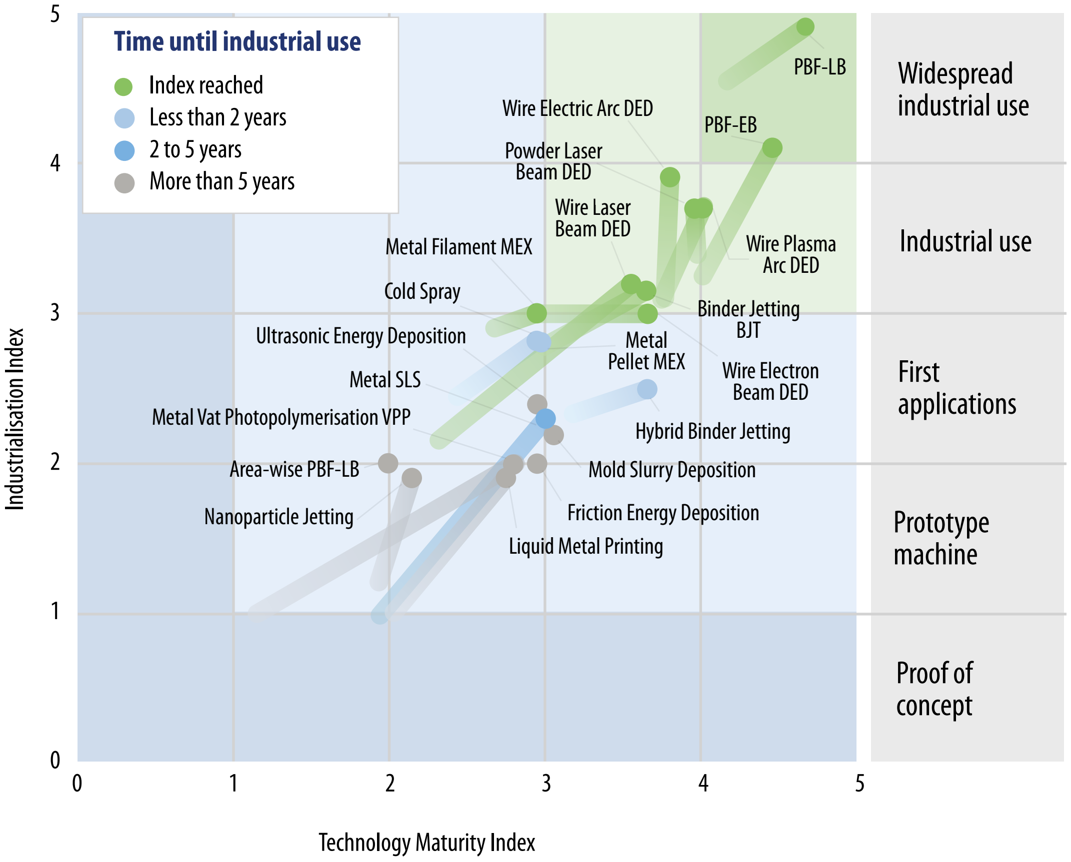


Figure 3. Maturity level of the most common Metal AM and the expected time until industrial maturity.(2)

1.3. Organizational Factors

The size of the company is a critical factor in implementing AM. Studies show that **adapting the organizational structure** is necessary to implement a new manufacturing process. This adaptation can be done in different ways: through the creation of a verticalized department, the creation of a transversal department, or simply by changing the duties of existing positions.

The company's organizational culture defines the complexity of acquiring new knowledge. Design for Additive Manufacturing (DfAM), brings a range of **new design techniques**, which should be incorporated into its *modus operandi*.

> A FERA survey of German toolmakers shows that around 60% of companies invest in AM training for existing employees rather than hiring new ones.

1.4. Operational Factors

Unique characteristics of additive manufacturing demand **new design and operating considerations**. These considerations have a **direct impact** on the industry's production planning and control. Authors focused on identifying strategies for additive manufacturing production planning raise the following criteria: part orientation strategies, build volume definition strategies, layer strategies, and support minimization strategies. It is worth noting that such planning must include costs regarding operating times, machines, personnel, and materials (Figure 4).

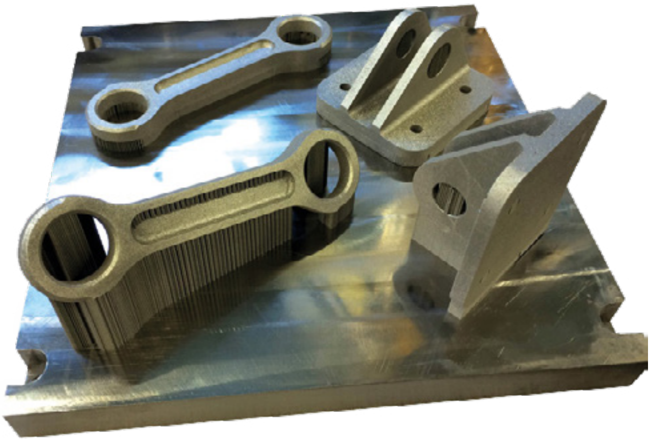


Figure 4. The importance of part orientation strategies on support minimization and production planning.(3)

In the context of additive manufacturing, studies point out a concept of near-net shape (NNS) process. This concept reflects the search for manufacturing methods in which the part meets the needs of quality control directly, without the need for post-processing. It is known that many AM processes are not yet at a level of maturity that meets the NNS concept. Therefore, finishing processes must be used. For strategic purposes, it is important to adapt the shop floor to carry out all the processing stages, not just deposition (Figure 5).

Figure 5. Finishing processes on an AM part. Near-net shape (NNS) focused studies tend to minimize post-processing needs.(4)

1.5. Supply Chain Factors

There are **two major supply chains** in additive manufacturing: the equipment supplier, who often also tends to supply raw materials, and the customer, who then becomes the supplier of this technology. **Achieving the full potential** of a growing technology depends directly on the engagement between the interested parties. The collaboration of equipment vendors becomes a critical point for successful implementation.

The method to implement additive manufacturing will be **different for each industry**. The most important point is to know that there is a way to implement this technology and take advantage of all the benefits that it can bring. This textbook shows the **path that project FERA** followed to spread the **AM culture** to **26 companies** since the understanding of different technologies, the importance of raw materials, process parametrization, and the concept of Design for Additive Manufacturing. All this information is essential to understand the **capabilities of AM**, to implement it in the industry.

2. AM Technologies

M.Sc. Lucas de Campos Bastos Carolo; M.Sc. Thiago Gomes de Cerqueira

According to the International Standards Organization (ISO), additive manufacturing (AM) technologies involve the “process of joining materials to make parts from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing and formative manufacturing methodologies.” (ISO ASTM 52900).⁽⁵⁾

The field of **Metal Additive Manufacturing** technologies is in constant evolution. There are currently **20 distinct operational principles** and an impressive array of over **190 equipment manufacturers** to date. Among these technologies, L-PBF and L-DED techniques stand out, both with a wide range of machine manufacturers. In the industrial sector, the L-PBF technique has been prominent, boasting the largest installed base of machines in the industry, surpassing all other available techniques, as exemplified in Figure 6. To effectively address an engineering challenge, it is imperative to understand all the available options. Ultimately, the selection of the appropriate technology should be guided by the specific application at hand.

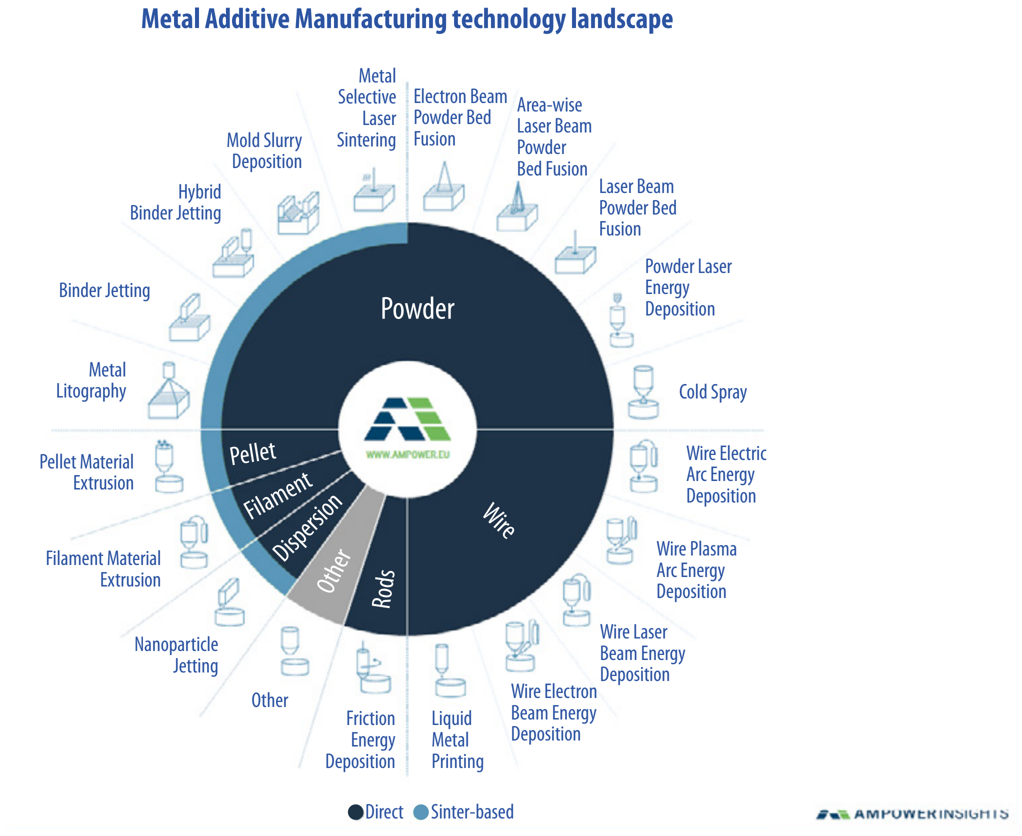


Figure 6. Overview of additive manufacturing technology and equipment suppliers.⁽²⁾

Achieving success in the implementation of Metal Additive Manufacturing requires an **understanding of the printing process and its intricacies**. Furthermore, it is essential to take into consideration factors such as design, production chain, application, and cost structure. But, selecting the right technology for the application is an essential step. It is therefore extremely important to know the technologies, with their respective capabilities and limitations. This layer-by-layer additive process can be achieved in many different ways. The ISO ASTM 52900⁽⁵⁾ describes the main AM techniques into 7 groups:

2.1. Vat Polymerization

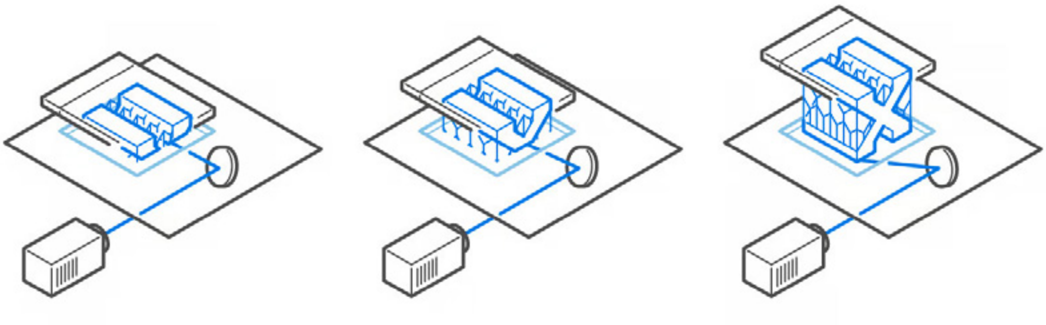


Figure 7. Vat polymerization process.(6)

Processes in which layers of liquid photopolymers in a vat are selectively cured through light-activated polymerization. The energy sources for curing can include lasers and LED projectors.

Commercial technologies

- Stereolithography (SLA)
- Masked stereolithography (MSLA)
- Digital light processing (DLP)
- Continuous digital light processing (CDLP)

Materials

- Polymers (liquid resin)

Common applications

- Rapid prototyping, consumer products, casting molds, medical devices (odontology)

2.2. Material Extrusion

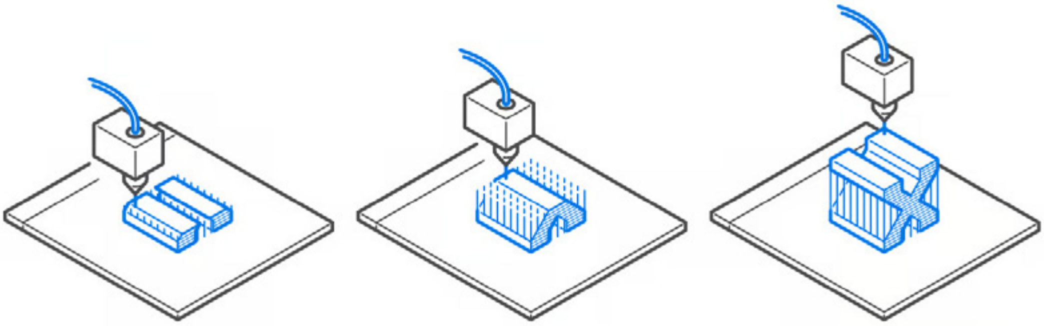


Figure 8. Material extrusion 3D printing process.(6)

Material extrusion additive manufacturing, also known as fused deposition modeling (FDM) or fused filament fabrication (FFF), is a 3D printing process that builds objects layer by layer by extruding a thermoplastic filament through a heated nozzle.

Commercial technologies

- Fused deposition modeling (FDM)

Materials

- Polymers, composites (thermoplastic filaments)

Common applications

- Rapid prototyping, end-use products such as jigs and fixtures

2.3. Powder Bed Fusion

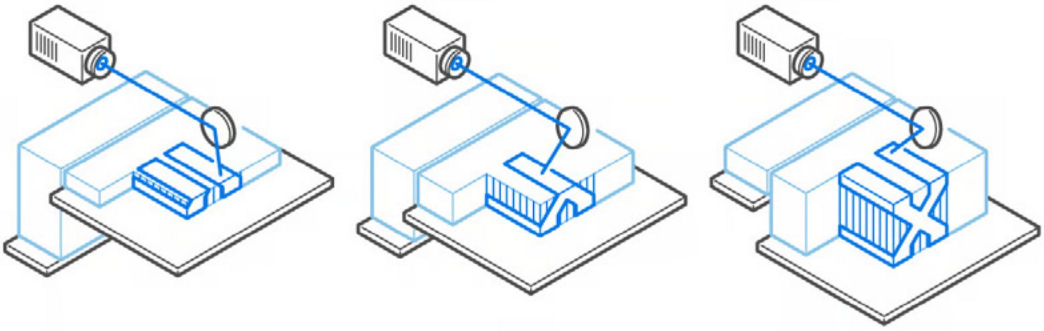


Figure 9. Powder bed fusion process.(6)

Process that starts with a thin layer of powdered material, which is spread evenly across a build platform. A high-energy heat source, such as a laser or an electron beam, is then precisely directed at specific points on this powdered layer according to the digital 3D model. The heat source melts or fuses the powder particles at these locations. Once a single layer is completed, the build platform is lowered slightly, and a new layer of powder is deposited over the previous one.

Commercial technologies

- Selective Laser Sintering (SLS)
- Direct Metal Laser Sintering (DMLS)
- Selective Laser Melting (SLM)
- Electron Beam Melting (EBM)

Materials

- Polymers (powder), metals (powder)

Common applications

- Fully functional parts, injection molding tooling with conformal cooling

2.4. Material Jetting

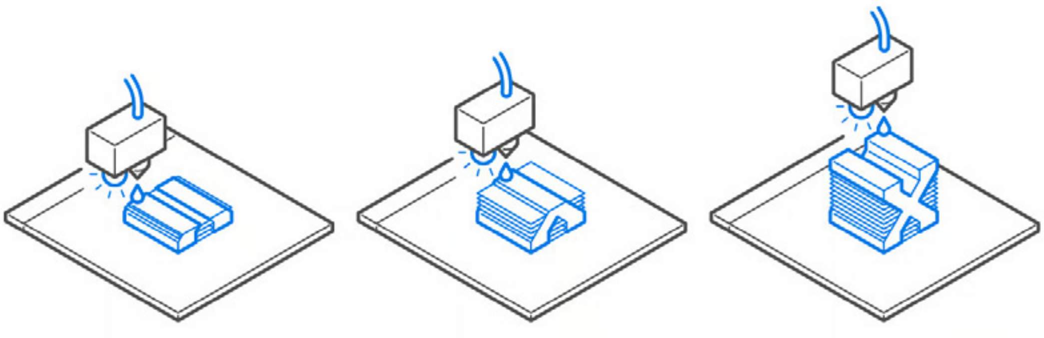


Figure 10. Material jetting process.(6)

A process that employs a printhead or multiple printheads to jet fine droplets of liquid material, often photopolymer resin, onto a build platform. These droplets are selectively deposited at specific locations based on a digital 3D model. Immediately after deposition, a UV light source or another curing method is used to solidify or cure the deposited material, bonding it to the previous layer.

Commercial technologies

- Polyjet
- NanoParticle Jetting (NPJ)
- Drop On Demand (DOD)

Materials

- Polymers (liquid resin), wax

Common applications

- Full-color prototyping

2.5. Binder Jetting

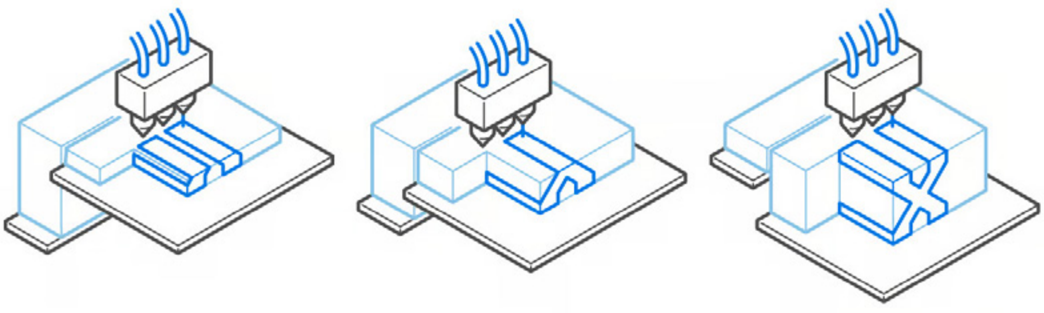


Figure 11. Binder jetting process.(6)

Process that begins with a powdered material, typically metal, ceramic, or sand, spread in a thin layer on a build platform. A print head moves over the powdered layer, depositing a liquid binding agent onto the material at specific locations, following the instructions of a digital 3D model. The binding agent adheres the powdered particles together, creating a solidified layer. After the printing is finished, the green part (the part made of bound powder) may undergo additional post-processing steps, such as sintering (for metals and ceramics) or infiltration (for metals), to further strengthen and densify the final part.

Commercial technologies

- Binder Jetting, Multi Jet Fusion

Materials

- Polymers (powder), metals (powder), ceramics (powder), sand, among others
- Liquid bonding agents

Common applications

- Fully functional parts, full-color prototyping, casts and molds, high manufacturing volume applications

2.6. Sheet Lamination

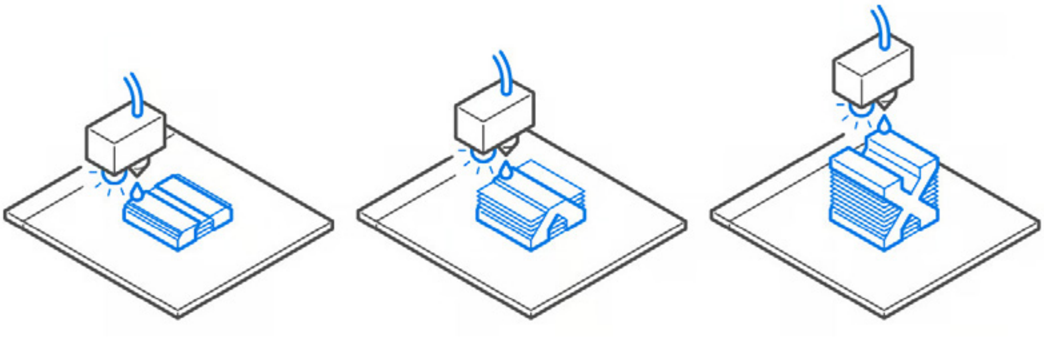


Figure 12. Sheet lamination process.(6)

Process that starts with a stack of thin sheets of material, often paper or plastic. A digital 3D model is used to guide a laser, adhesive, or heat source, which selectively bonds or fuses specific regions of each sheet.

Commercial technologies

- Laminated Object Manufacturing (LOM)
- Ultrasonic Consolidation (UC)

Materials

- Paper (sheet), composites (sheet), metals (sheet)

Common applications

- Full-color prototyping, molds

2.7. Direct Energy Deposition

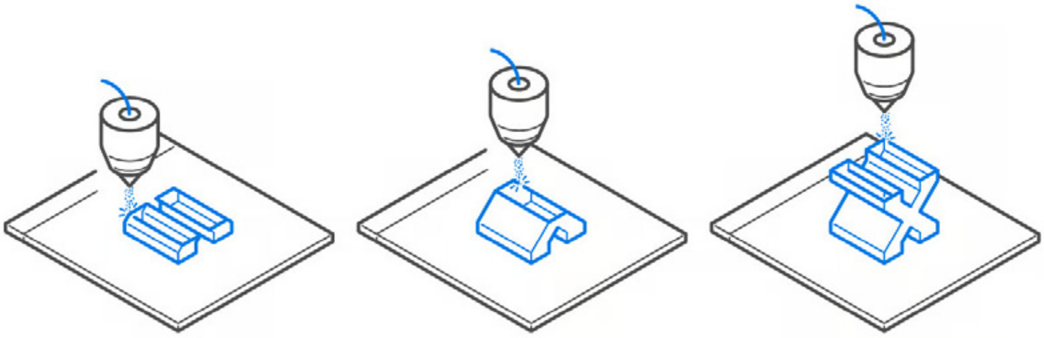


Figure 13. Directed Energy Deposition process.[6]

Process that utilizes a high-energy source, typically a laser or an electron beam, to melt and fuse material, often in the form of wire or powder, as it is precisely deposited onto a substrate or an existing workpiece. The energy source is focused on the deposition point, rapidly melting the material and creating a bond with the substrate. The process is controlled by a digital 3D model, which guides the movement of the energy source and the material deposition nozzle or powder nozzle.

Commercial technologies

- Wire Arc Additive Manufacturing (WAAM)
- Laser-Directed Energy Deposition
- Electron Beam-Directed Energy Deposition

Materials

- Metals (powder)

Common applications

- Fully functional parts, repairs

Selecting the correct additive manufacturing technology for a specific application is paramount to the **success of the process of implementation** of the technology. Each additive manufacturing process, whether it is Fused Deposition Modeling (FDM), Stereolithography (SLA), Selective Laser Sintering (SLS), or others, comes with its unique set of capabilities, limitations, and material compatibility. Selecting the right technology ensures that the desired material properties, resolution, surface finish, and mechanical strength are achievable, aligning with the application's requirements. Moreover, it can impact factors such as production lead time, cost-efficiency, and scalability. An information-based selection in additive manufacturing technology not only optimizes the **production process** but also opens up possibilities for **innovative designs** and the creation of **customized, high-performance** parts that would be challenging or impossible to produce using traditional manufacturing methods. Thus, it is essential to **carefully evaluate** the demands of the application and match them with the capabilities of the selected additive manufacturing technology to achieve the most appropriate results.

In addition to selecting the right additive manufacturing technology, the definition of the material is equally critical in determining the success of any additive manufacturing application. The material not only defines the physical and mechanical properties of the final product but also influences operational factors such as durability, thermal resistance, chemical compatibility, and even surface quality. Furthermore, it can impact post-processing requirements, cost considerations, and the overall feasibility of the project. Thus, an informed and thoughtful selection of the material is pivotal in harnessing the full potential of additive manufacturing for a given application.

3. What about Materials?

Eng. Giovanna Fiocco Colombo; M.Sc. Moysés Leite de Lima

Dealing with materials for AM processes involves the evaluation of different technical and economic aspects. Besides, **raw material properties** and their relation with process parameters **can affect the final product quality decisively**. In this perspective, the specification and control of the raw material properties are essential to obtain reproducible results in AM processes.

The alloy definition is related to the final product requirements, and materials selection methods are valuable for this task. Further, the alloy availability for each AM process is an important point to be considered nowadays for the selection of materials, including the raw material form (powder or wire). For the processes that use powder as raw material, the next step would be the **specification of the particle size** distribution, which **depends on the AM processes** (PBF or DED, for example) and the equipment requirements.

Once the raw material is specified and received, a general material characterization should be conducted aiming the process control and results traceability. As an example, this general characterization of a powder as a raw material consists of the following steps, which will be further discussed in the following sections:

- Chemical composition.
- Particle size distribution.
- Particle morphology characterization.
- Particle surface characterization.
- Rheological behavior.

The AM process, technology, and equipment will **guide** the critical evaluation of the **powder characterization results**. For example, powder flow in L-DED equipment depends on the nozzle design, powder characteristics, and powder transport system and its parameters. Inadequate powder properties for a given cylinder head and powder transport system can lead to a discontinuous powder mass flow and, consequently, defects in the building part.

How Can the Powder Affect the Deposition?

Powder characterization for additive manufacturing processes should be related to how the powder is added to the part building. In the powder-bed fusion (PBF) technique, the metal powder is stored in a reservoir, it is transferred to the building level by some mechanism (gravity or platform), and it is spread over the building plate area creating a powder layer that is melted selectively according to the desired geometry. The **final part quality** is then affected by how homogeneous and uniform each layer is, so the **flowability and spreadability** of the powder are some properties that influence it.

Incorrect spreading can result in defects like streaking, inconsistent layer thickness leading to porosity, and other built flaws, as shown in Figure 14. Some powder characteristics such as particle size distribution, particle morphology, and external factors such as humidity, triboelectric charge buildup, processing history, and their effect on the deposition are well known. **Highly spherical powders** commonly result in **better flowability**, but there are **exceptions** to this, especially when the powders are extremely fine.

In general, the PBF technique requires powders with spherical particles within a size range between 20 and 53 µm with good flowability. In the direct energy deposition (DED) technique, the powder is usually transported to the nozzle using an inert gas, so a property called powder aeration became important. **Aeration** is measured as the powder's ability to be lifted by a gas flow from the bottom to the top of the container. In the powder-based DED, the powder characteristics influence the powder mass flow and its regularity along the process time. Insufficient powder on the pool melt can result in **defects** like inconsistent layers, and trapped gas leading to porosity, in the same way as the PBF technique. Highly spherical powders are also a requirement for this technique, typically with a particle size between 53 and 105 µm.

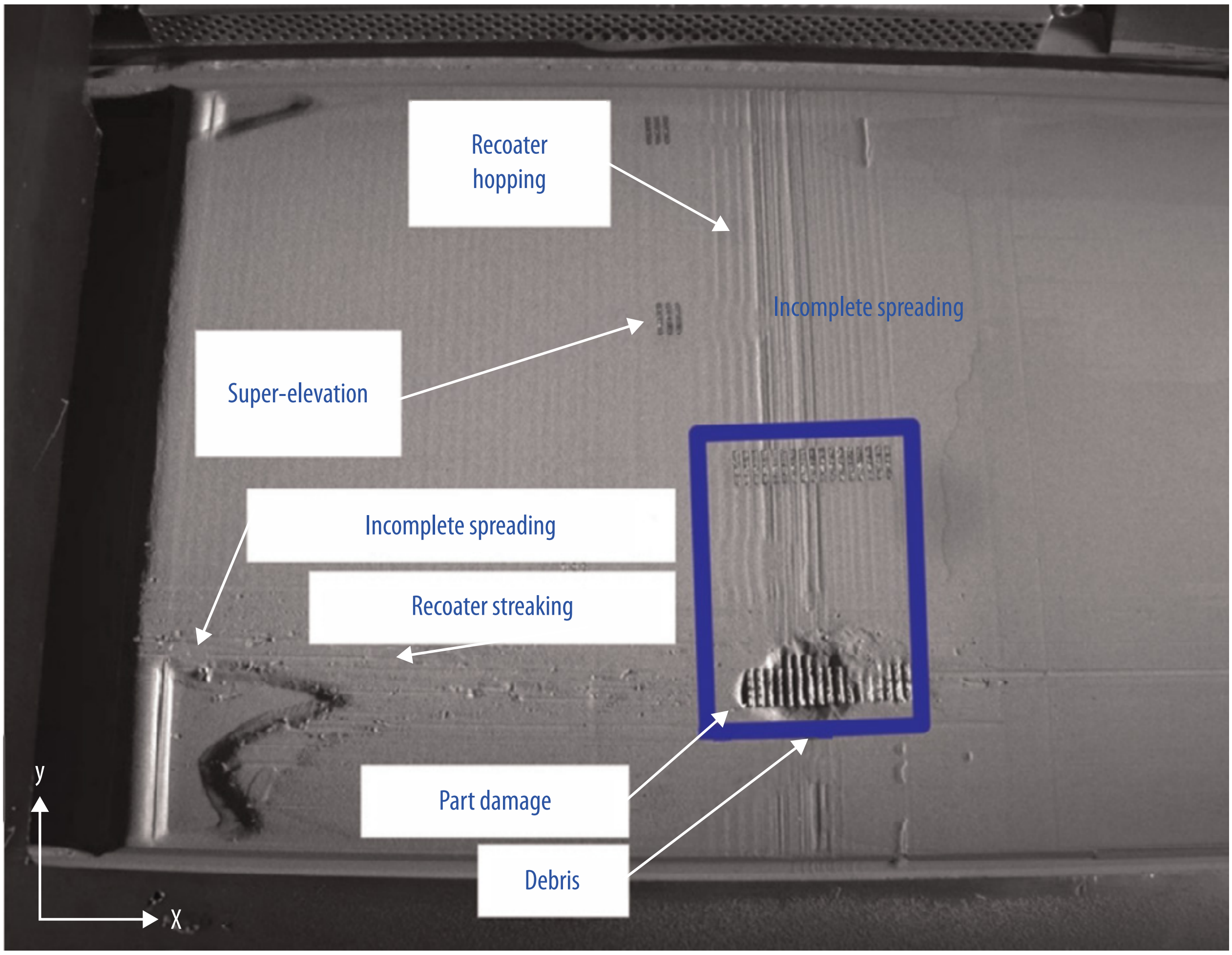


Figure 14. Possible defects caused by bad powder spreadability.(8)

There is no single experimental technique able to measure all properties of a powder and determine its general quality. Therefore, the flowability and other powder characteristics should be measured using different experiments. Then, these properties should be related to each other and to the AM process and equipment in which the powder will be used. As examples, in the following section, three techniques to characterize a powder for AM are presented.

3.1. *Hall/Carney* Flow Test

The *Hall* flowmeter funnel is used to measure the powder mass flow rate, which indicates the powder flowability. The experiment consists of pouring a specific quantity of powder into the funnel (Figure 15) and measuring the time required for the powder to flow through the orifice. The ASTM International standard B213(9) indicates the experimental details. The first result of this experiment is answering the question: **Does the powder flow or not through the funnel**? If a powder does not flow through this funnel, its application in any additive manufacturing process usually faces difficulties. Besides, this **technique** can be used to compare the **flowability of different powders or a powder under several conditions**. The lower the time elapsed for a powder to flow through the funnel, the higher the flowability is.

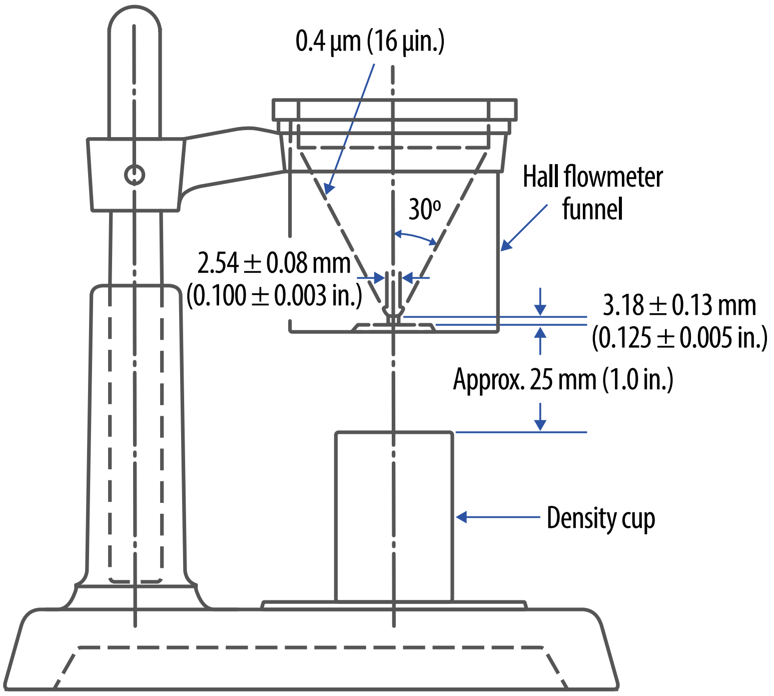
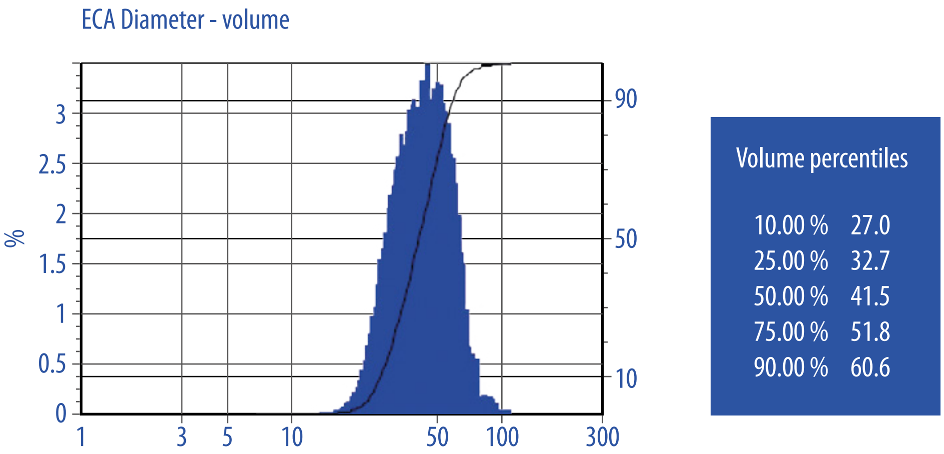


Figure 15. Hall flowmeter geometry.[9]

3.2. Powder Size Distribution and Morphology

Depending on the additive manufacturing process and equipment, a **particle size range** is required, as described before. Different techniques can measure the powders' particle size distribution, such as laser diffraction, *Fisher* analysis, dynamic image analysis, and microscopy. Among these techniques, those that involve image processing are the only ones that allow further measurements, such as morphology and surface analysis. Figure 16 and Figure 17 shows the results of particle size and morphology distributions for the 316L powder used for the L-PBF process in the FERA project obtained using **dynamic image analysis**. With this technique, the principal results associated with the **particle morphology** are the circularity and the smoothness.



Volume percentiles

10.00 %	27.0
25.00 %	32.7
50.00 %	41.5
75.00 %	51.8
90.00 %	60.6

Figure 16. Powder size distribution in volume. The result was obtained on the Particle Insight Analyzer for a 316L SS powder for the L-PBF process.

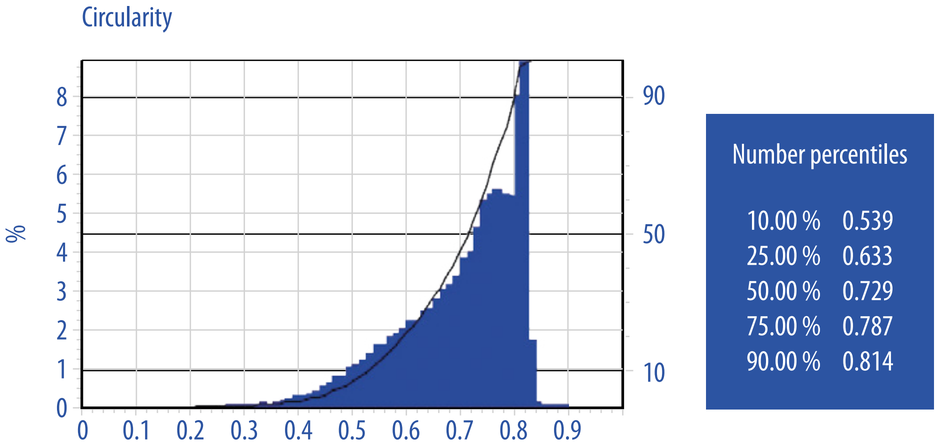


Figure 17. Circularity distribution result obtained on the Particle Insight Analyzer for a 316L SS powder for the L-PBF process.

These characteristics can also be analyzed using images acquired in a scanning electron microscope (SEM), with which it is possible to **quantify defects** such as satellites, broken or elongated particles, and other malformations (Figure 18). Those powder characteristics should be related to the available AM equipment. The knowledge about the AM process and the experience with specific equipment is fundamental to establishing the relationships between the powder characteristics and the effects on a built-part experience and data analyses.

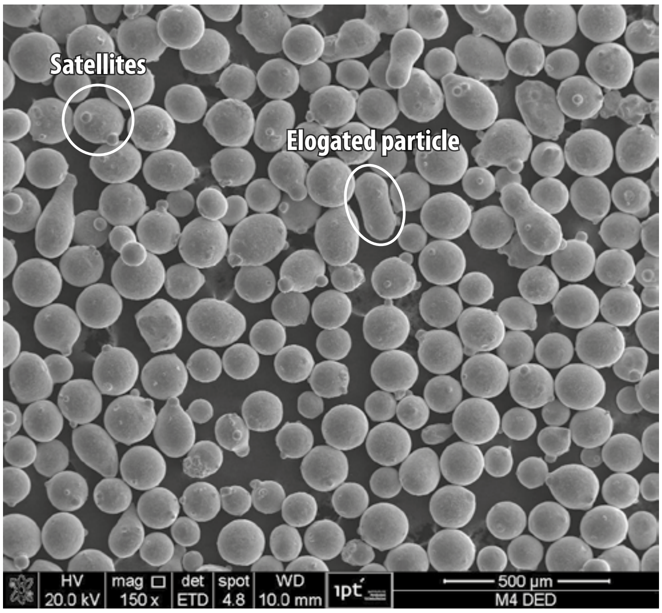


Figure 18. SEM of the AISI M4 toll steel powder for the L-DED process.

3.3. Rheology

Powder rheology is also an important tool for evaluating **flowability**. It is possible to study the powders' flowability under several conditions by experiments conducted in a powder rheometer. Some of these experiments can reproduce those conditions observed in the AM equipment. The possibilities of experiments using an FT4 powder rheometer will be presented here as an example.

With this powder rheometer, one can divide at least experiments and properties into **three categories**: bulk, dynamic, and shear. The main bulk properties are conditioned bulk density (CBD), compressibility, and permeability.

First of all, powder conditioning is a procedure conducted in the rheometer to **avoid the effect of the previous powder handling or processing** (packing, aeration, etc.). This procedure ensures that the powders are analyzed with similar initial conditions. Therefore, conditioned bulk density (CBD) is the powder density packed into the cylindrical glass vessel measured after a conditioning cycle. **Compressibility and permeability** can be considered indirect measures of flowability relating to process environments, such as storage in a hopper or, less directly, roller compaction. The **dynamic flow** properties are related to the stability and interaction between the particles and result in some key parameters, such as cohesion and shear strength. For example, the cohesion between the particles influences the powder spreadability in the L-PBF process.

Basic flowability energy (BFE) and **specific energy** (SE) are the first measurements to understand the **cohesion of a powder**. High energy indicates that the powder can **agglomerate** during the powder transport and spread or even not flow. Aeration measures the powder's ability to be fluidized by gas and is also an indication of cohesion. **High aeration energy** indicates that the powder is **trapping gas**, or the particles are agglomerated, and the powder does not fluidize. The powder behavior in a shear condition quantifies factors such as cohesion and flowability.

4. AM Parametrization: What has to be done before building components

PhD. Daniela Passarelo Moura da Fonseca; M.Sc. Henrique Rodrigues Oliveira; M.Sc. Bruno Henrique Oliveira de Lima

Achieving high-quality metal AM components has its challenges. The process of parameterization plays a pivotal role in addressing these challenges. Before delving into the specifics of parameter optimization, it is crucial to understand the typical defects that can occur in metal additive manufacturing.

The combination of **thermal and structural** phenomena creates a **high complexity** in terms of the **surface integrity** of a component built by AM. This complexity can be evidenced by defects that appear during deposition. The most typical defects in AM are voids and porosities, cracks, keyholes, balling, and humping effects.

- **Voids and porosities** are any empty regions that can be formed within a single layer, between adjacent layers, and/or on the external surface. The main causes are entrapped gas porosity; incomplete melting-induced porosity, and; lack of fusion with unmelted particles inside large irregular pores.
- **Balling** effect appears when liquid does not spread to create a homogeneous layer as a result of surface tension, and instead, it rapidly solidifies into spherical features. It can appear in two different forms: Unmelted or partially-melted powder particles (appearing alone or in clusters) or Spatter particles in which molten material is ejected from the melt pool during beam traversal, impacting the nearby surface during solidification.
- **Humping** phenomenon happens due to the competition between surface tension (thermocapillarity) and flow inertia. To minimize the surface tension, the liquid bead breaks into separated droplets causing an accumulation of molten material.
- **Keyhole** defects primarily manifest as vapor cavities that result in depressions on the surface of the printed object. They are typically induced by high laser power density, from which a highly localized energy leads to deep penetration. These vapor cavities, often referred to as keyhole pores, become unstable and may collapse as the melt pool progresses. When the track solidifies, the trapped vapor cavity within it can lead to the formation of keyhole defects.

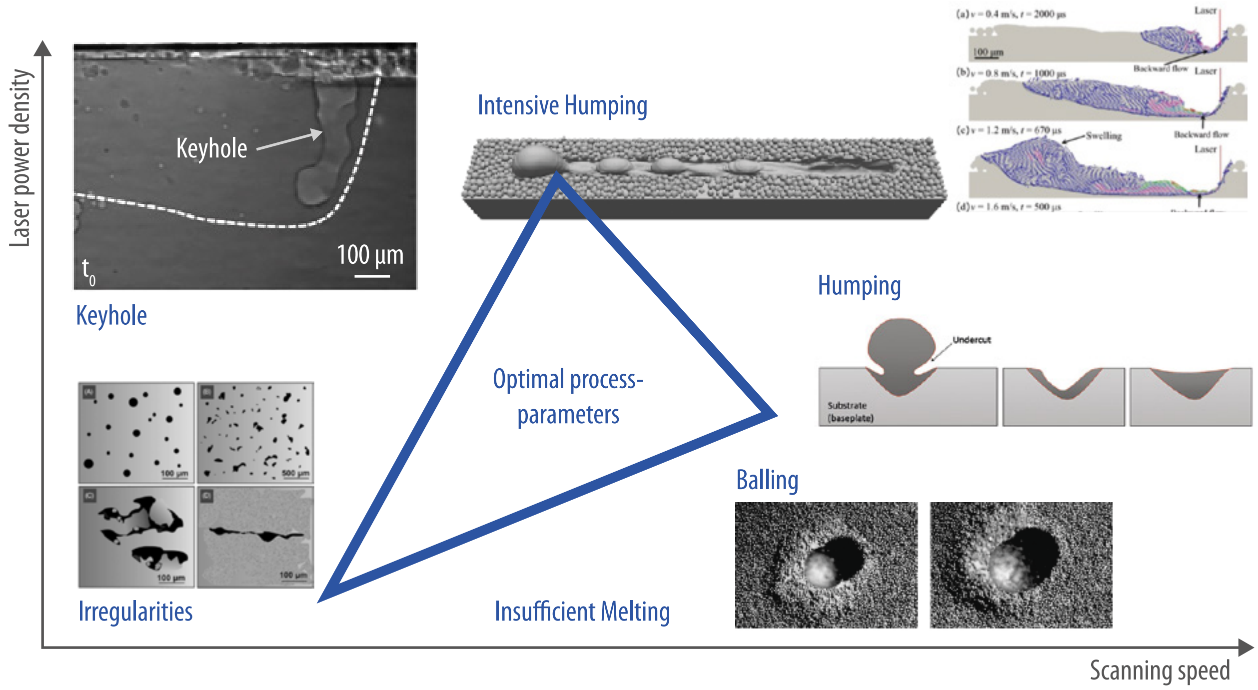


Figure 19. Necessary balance in the energy provided for melting the interface in order to avoid integrity defects.

To avoid all these and other kinds of defects is necessary to have a well parametrized AM process. In general, there are two different working scenarios to parametrize an additive manufacturing building process. The first is when the equipment does not give you the freedom to change the operational parameters like scanning speed or laser power. The other option is when it is possible to have access to modify different operational parameters. This means that operators can fine-tune settings like layer height, print speed, temperature, and material composition, among others. This flexibility is beneficial for advanced users and researchers who want to optimize the printing process for specific applications, materials, or quality requirements.

In scenario 1, the user of the technology has to do the quality control of the raw material. In scenario 2, in addition to the characterization of the raw material, the user also needs to perform the development of the processing parameters. In this section, the second case will be further addressed.

The main process parameters for laser powder bed fusion are:

- **Laser power:** the measured kilowatts or watts determine the intensity of the energy delivered by the laser source. Higher laser power allows faster melting of the powder material. It is crucial for controlling the depth of the melt pool, which affects the part's density and structural integrity. Lower power may result in incomplete melting, while excessive power can lead to overheating and defects.
- **Laser wavelength:** affects its interaction with the material. Different materials absorb and reflect different wavelengths of light. Selecting the appropriate laser wavelength is essential for efficient energy absorption and controlled melting of the material.
- **Laser beam diameter:** The diameter of the laser beam at the focus region influences the size and geometry of the melt pool. A smaller beam diameter allows for finer details and higher resolution in the printed part, while a larger beam diameter may be used for faster printing but with reduced detail.
- **Laser scanning speed:** This parameter determines how quickly the laser moves across the powder bed. The scanning speed affects the amount of energy delivered to each spot, which in turn impacts the material's temperature and solidification rate. Controlling scanning speed is crucial for achieving the desired material properties and surface finish.
- **Laser scanning strategy:** The path that the laser follows during fabrication is known as the scanning strategy. There are various strategies, such as contour-parallel, island, or raster scanning. The definition of the strategy impacts factors like build time, heat distribution, and part distortion. Optimizing the scanning strategy is

essential for achieving uniform melting and reducing thermal stress.

- **Hatch distance:** Hatch distance refers to the spacing between two adjacent laser scan tracks. It influences the overlap between scans, which can affect the part's density, surface finish, and mechanical properties. Properly adjusting the hatch distance is essential for controlling the part's quality.
- **Layer thickness:** The layer thickness determines the height of each deposited powder layer. A thinner layer provides finer resolution and smoother surfaces but may require more layers and time. A thicker layer can reduce build time but may result in a rougher surface finish. Layer thickness is critical for achieving the desired part geometry and surface quality.

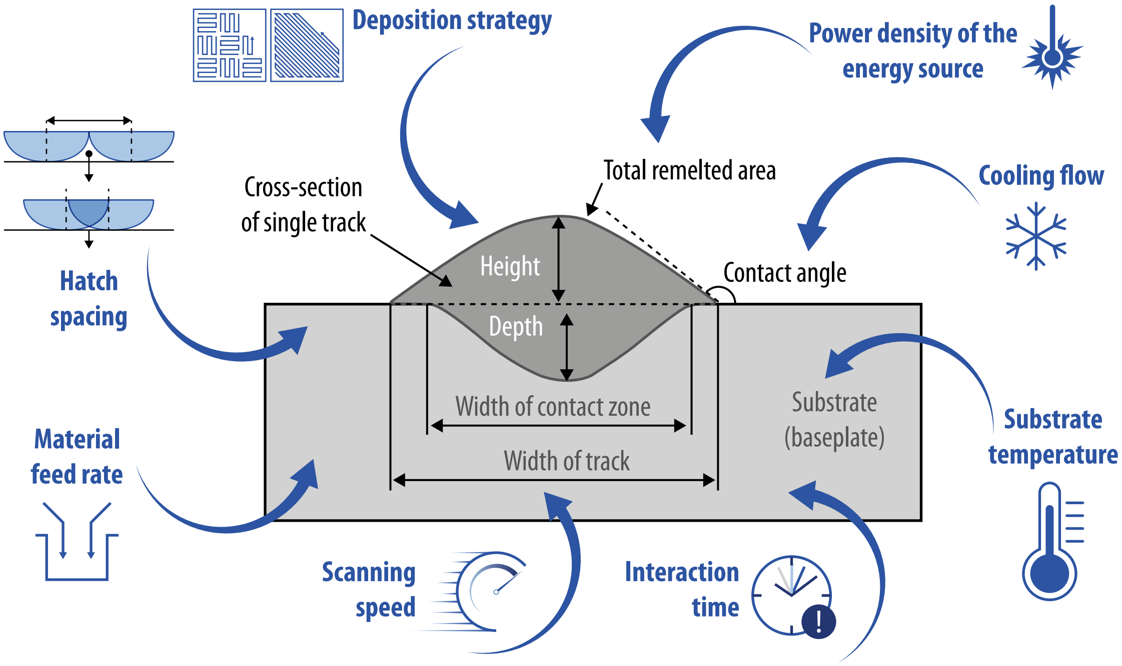
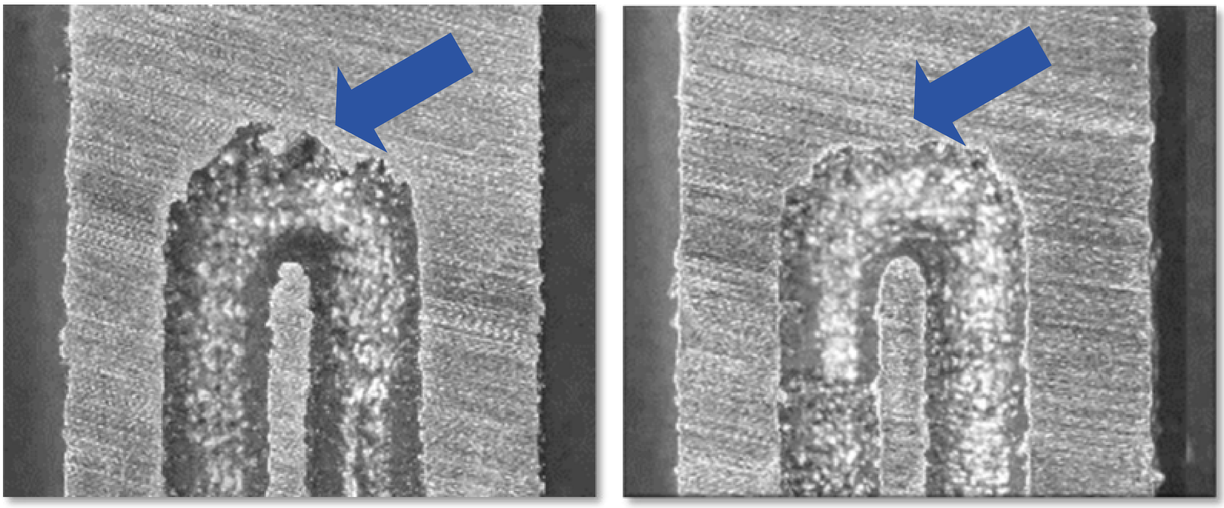


Figure 20. Process parameters and their impacts on the deposition.

The AM parametrization highly depends on the used technique. The following example is a sequence for **Laser Powder Bed Fusion** (L-PBF), in which the main parameters that eventually need to be developed are for (Figure 21):

Bulk: main region of the built parts. These parameters can affect mainly the density and the mechanical properties of the printed parts.

Contour: external region of the built parts. These parameters are used in conjunction with or complementary to the bulk parameter. Using the contour parameters, it is possible to obtain better control of dimension and surface geometry, especially in internal channels. Figure 14 exemplifies the demonstrator developed during the project FERA for a conformal cooling application with and without contour parameters.



Component with internal cooling channel built **without** the contour parameter

Component with internal cooling channel built **with** the contour parameter

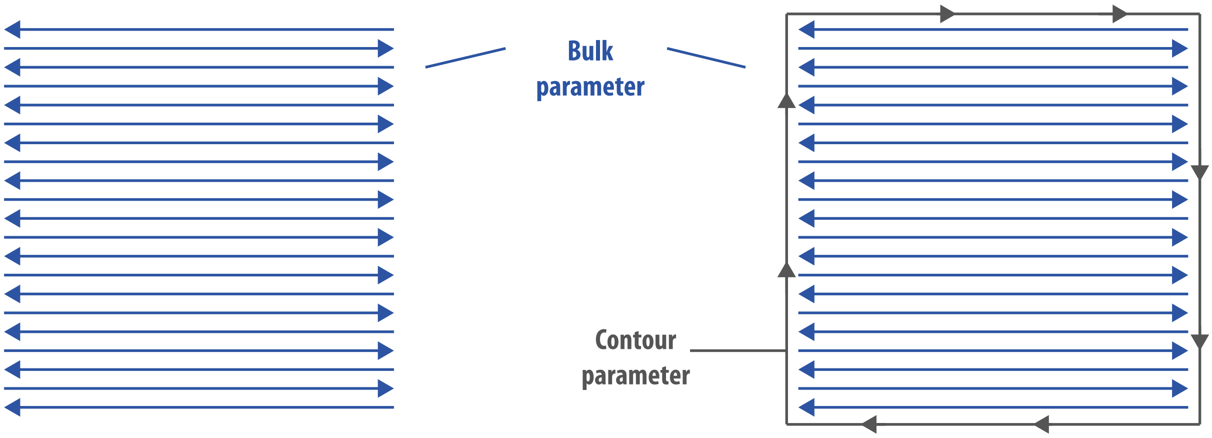
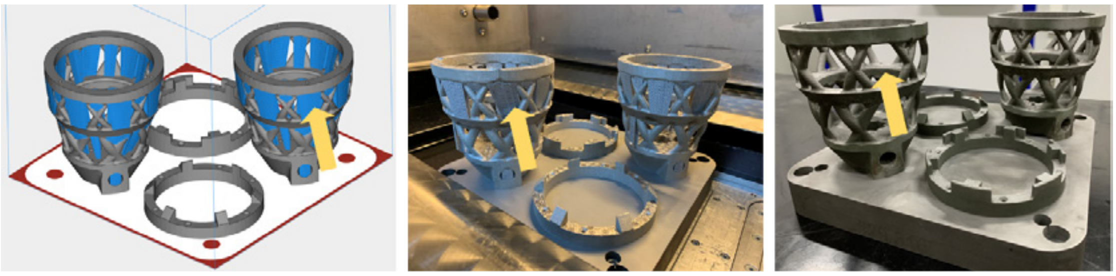


Figure 21. Difference between bulk and contour parameters in a conformal cooling application developed during project FERA.

Support structures: Support structures are auxiliary elements that are generated during the manufacturing process to provide stability and prevent distortion or collapse of overhanging or complex geometries. These structures are later removed or post-processed after the printing is complete (Figure 22).



Support structures in components of complex geometries

Components after removing of support structures

Figure 22. Example of support structures application (Blue regions). Fixtures and Jigs demonstrator developed during project FERA with the application of the DfAM concept obtaining the result of 47% mass reduction.

Figure 23 illustrates three distinct sequences for the parametrization of different specimens specifically focusing on the production of specimens for density and tensile strength analysis. The sequence specifies first the scanning strategy, definition of the process parameters, manufacturing plan, manufacturing of the specimens, post-processing, and finally the analysis itself.

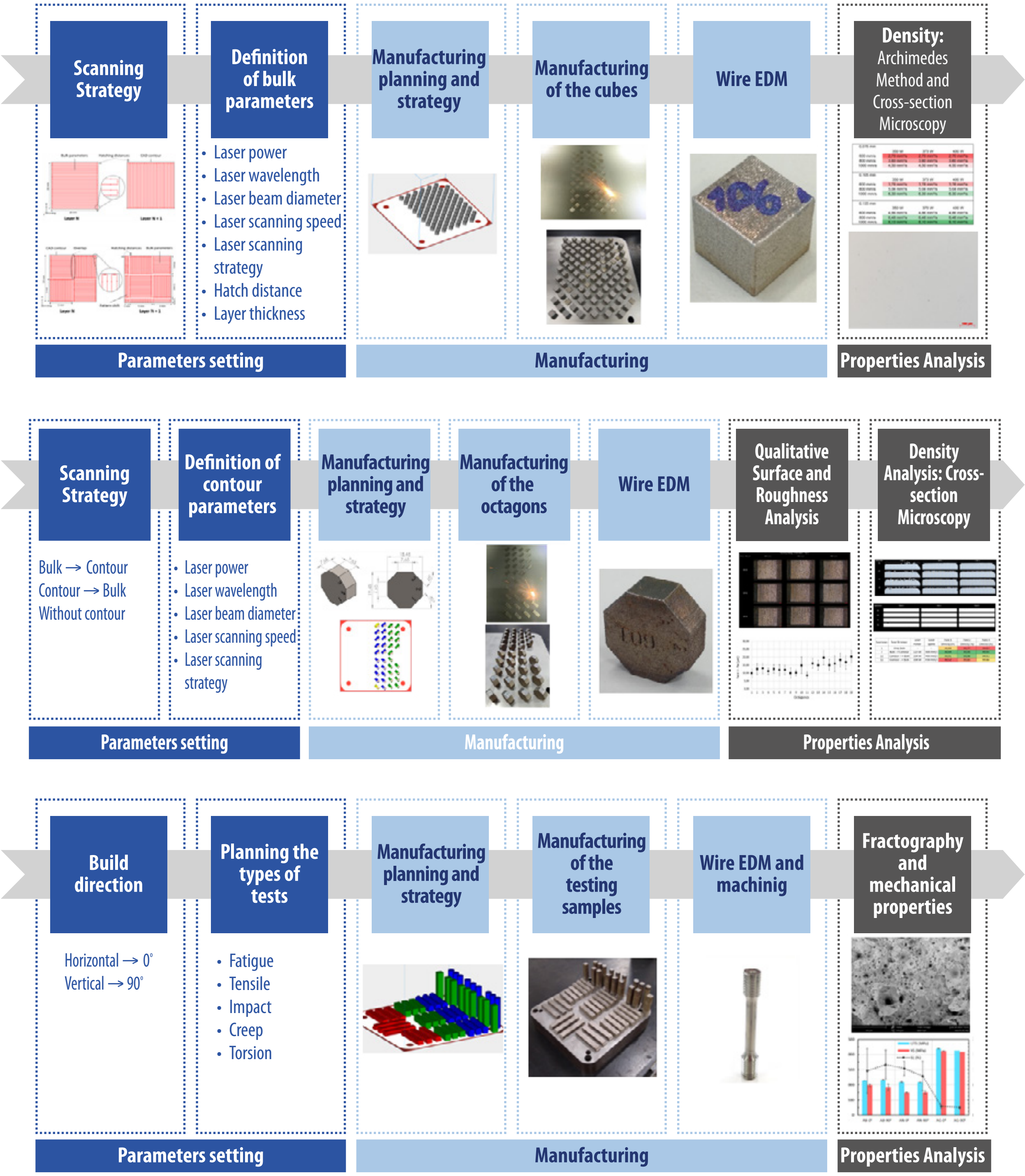


Figure 23. Parametrization sequence for different specimens of density and mechanical properties analysis.

5. And After the Deposition?

M.Sc. Bruno Henrique Oliveira de Lima; Prof. Dr. Ronnie Rodrigo Rego

Additive Manufacturing (AM) has revolutionized the manufacturing industry with its ability to produce **complex and customized components**. However, the objects generated through AM processes are often characterized by structure inhomogeneities and poor topography, despite a tensile and **heterogeneous state of residual stresses** (RS), Figure 24. In order to extract the best potential of this manufacturing chain, post-processing techniques are conducted to achieve the desired functionality of the components.

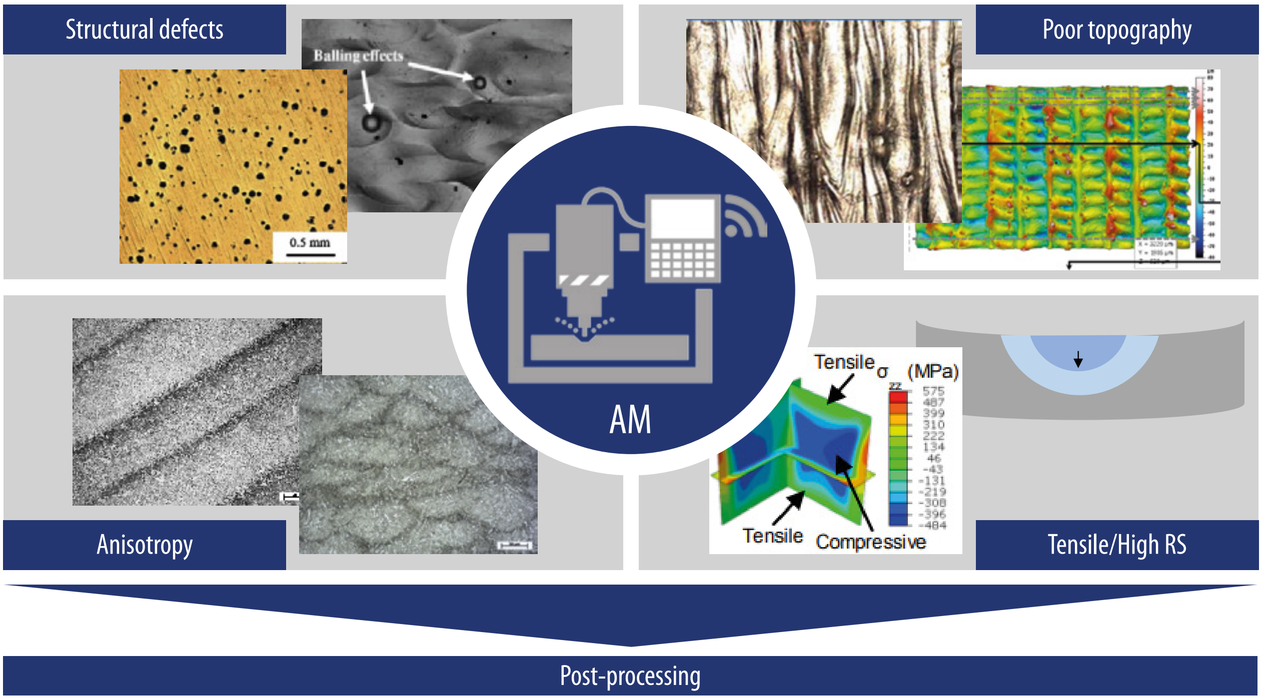


Figure 24. Demand for post-processing to achieve required functionalities.

This essay delves into some examples of post-processing alternatives available for components built using additive manufacturing.

5.1. Machining

One of the most common post-processing methods is machining. This involves the removal of excess material to refine the dimensions, achieve a **smooth surface** finish, and **enhance tolerances**. While it can be a subtractive process, it is particularly useful for metal AM components that require **precise geometric features**. Depending on the component, the geometric tolerances cannot be achieved by the AM process, in this case, a machining process will be necessary to achieve the final dimensions (Figure 25). Considering the complex geometries that can be created by AM, a challenge that can be faced is the clamping of the component. Another aspect to consider is that the rapid cooling caused during deposition in processes such as L-PBF and L-DED tends to induce high hardness and heterogeneous microstructures. This characteristic can induce more pronounced wear on cutting tools when compared to machining operations using similar alloys but manufactured using conventional processes such as casting and rolling.

5.2. Finishing

Post-processing techniques like vibratory finishing, abrasive flow machining, and chemical smoothing can be employed to **improve surface quality**. Vibratory finishing uses abrasive media and liquid to remove irregularities and create a uniform surface. Chemical smoothing, on the other hand, involves immersing the component in a chemical bath to dissolve surface imperfections. The **topography obtained from additive manufacturing** tends to have a **high heterogeneity** of roughness peaks and valleys creating challenges for processes like vibratory finishing and polishing.

5.3. Heat Treatment

Heat treatment processes like annealing and stress relieving can be used to enhance the mechanical properties of AM components. Annealing tends to homogenize the microstructure and improve ductility, while stress-relieving tends to homogenize the residual stresses, but it will not eliminate it, minimizing warping or cracking in the final part. Each parameter decision implies different impacts on the RS state, and it needs to be addressed to evaluate the impact on the component's life. The **heterogeneous residual stress state** brings the complexity of dealing with the resulting **distortions** during heat treatment. In some situations, it may be necessary to increase the stock material to compensate for a higher level of distortions during the deposition or heat treatment.

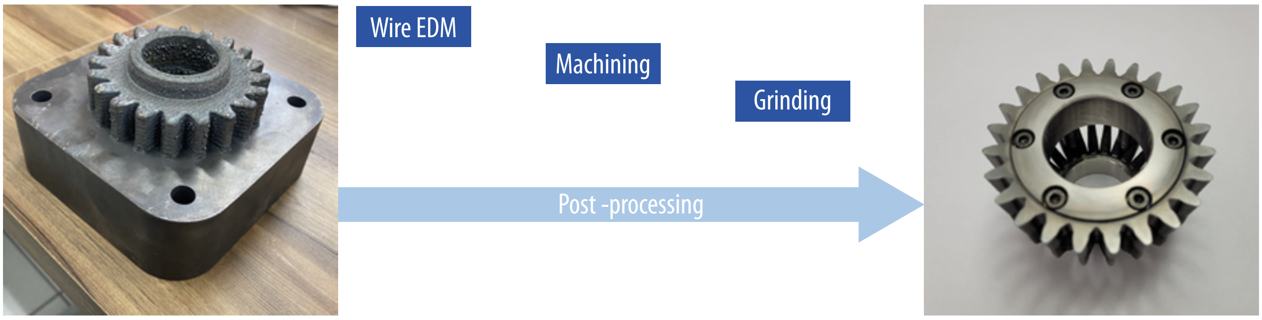


Figure 25. Shaping cutting tool developed and manufactured during project FERA.

Figure 26 summarizes different techniques that can be **applied to post-process** a component produced by additive manufacturing. The chosen process will depend basically on the **application** that the component will be submitted, and the AM process used to produce it. Components produced by L-DED for example will almost always have to go through a machining process due to the topography of the surface obtained in this process, whereas samples manufactured by L-PBF machining steps may not be necessary depending on the application.

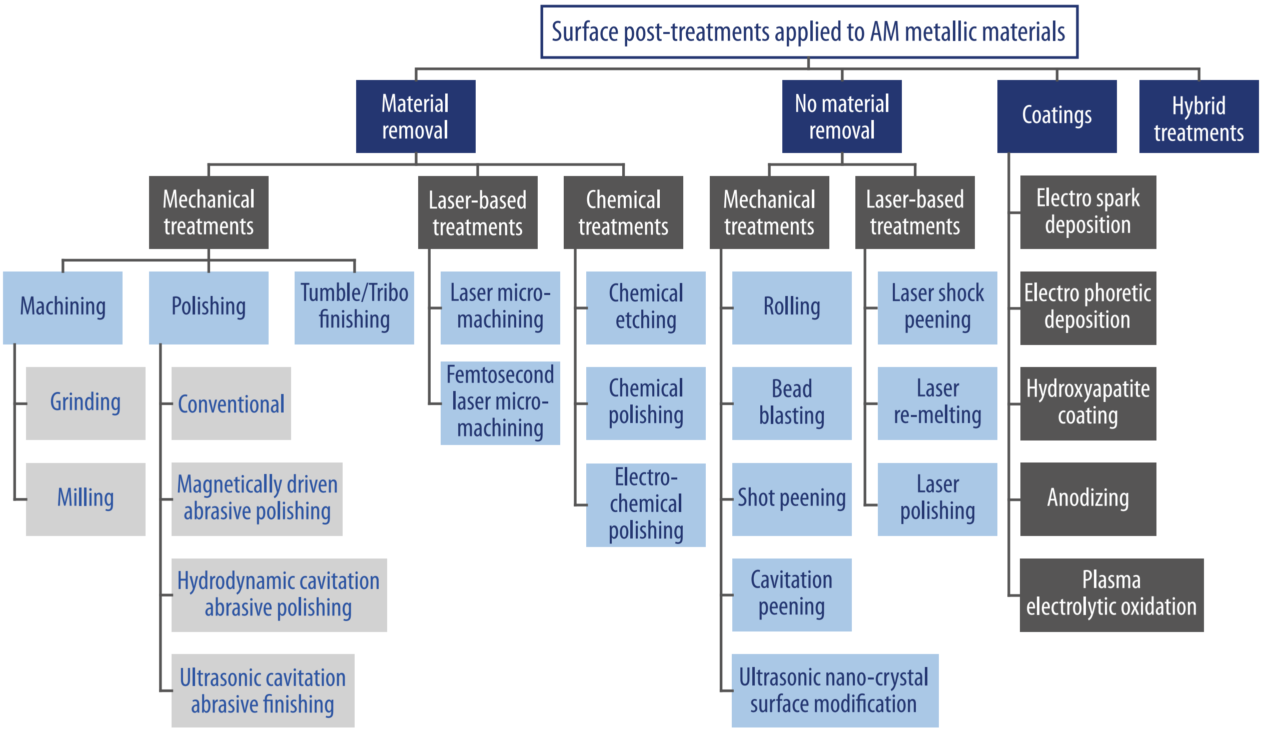


Figure 26. Categorization of the surface post-treatments applied to AM metallic materials.[(7)]

Post-processing is a crucial step in the additive manufacturing process, allowing for the optimization of components for their intended applications. The choice of post-processing method depends on the material, the part's geometry, the desired properties, and the specific industry requirements. The continuous development of post-processing techniques and the integration of automation and digital technologies are expected to further refine and expedite the post-processing of AM components, expanding the capabilities and applications of additive manufacturing in various industries.

6. Design for Additive Manufacturing

Eng. Matheus Rubik; M.Sc. Guilherme Fernandes Guimarães

The unique characteristics of additive manufacturing require particular resources. Design barriers created by years of experience in conventional manufacturing techniques must be broken down.(10)

Among the main advantages of additive manufacturing are the high freedom of design combined with customization, the possibility of low production volumes, and similar or better mechanical performance when compared to various cast materials,(11) which are fundamental for the better performance of additive manufacturing compared to conventional manufacturing.

Additive manufacturing allows the creation of **complex geometries** on external and internal surfaces, for example, conformal cooling channels that follow the external geometry, and the joining of several parts that, by conventional manufacturing, require sub-assemblies. Nevertheless, the possibility of adding material at specific points of the component to **increase its strength** is highly effective and helps to **lightweight** the component.

> “
>
> This tool’s unconventional design is from **another world**.”
>
> *Engineer feedback*

The concept of **Design for Additive Manufacturing** (DfAM) is a systematic approach that empowers creators to not only conceive, but also refine, modify, and elevate the structure and purpose of a specific component, assembly, or even an entire product. This methodology is strategically hinged upon harnessing the myriad benefits inherent to additive manufacturing processes. This approach integrates design intricacies with the **unique capabilities of additive manufacturing**, DfAM brings forth a paradigm where every facet of a part or product is meticulously tailored to unlock the full spectrum of advantages offered by this manufacturing technique. To apply the DfAM concept, it is necessary to follow some steps as shown in Figure 27.

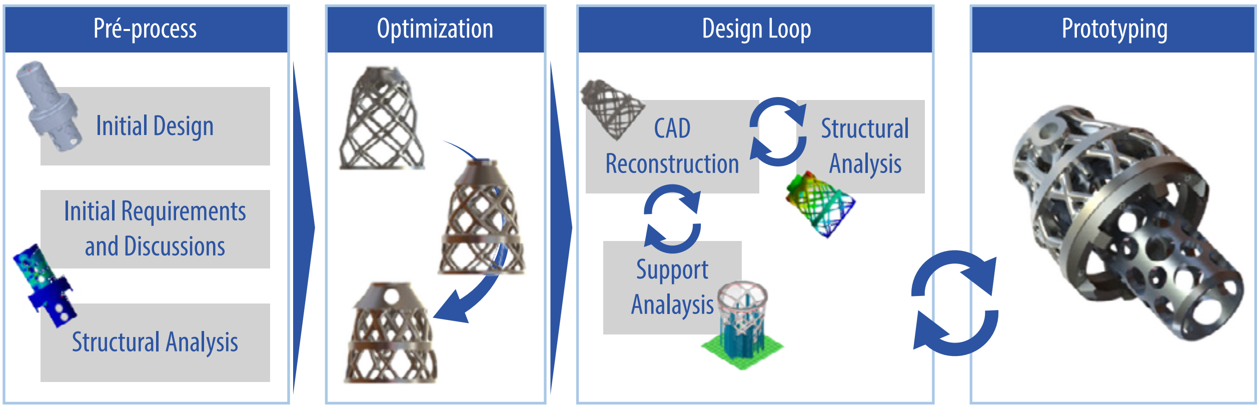


Figure 27. Design for additive manufacturing development flow.

> “The new tool was incorporated into the production line **effectively replacing the conventional tool** and **improving** operator **ergonomics**.”
>
> *Engineer feedback*

The process starts with the **requirements analysis**, where the original CAD files of the component are reviewed and the initial requirements for the part are defined. Characteristics such as the torque to which the part will be subjected, material, the required mass reduction, and others need to be considered during the design phase.

Once the **constraints and boundary** conditions have been **precisely defined**, the next step involves the creation of a simplified geometry tailored for simulation purposes. This geometry serves as a virtual representation, allowing for a comprehensive examination and validation of the various conditions to which the particular component is exposed. Through this **simulation-driven approach**, the behavior and performance of the part under diverse scenarios can be thoroughly evaluated, enabling informed design decisions and optimizations.

The next step is topological optimization, Initially, the design space and the objective are defined, which can be different depending on the component and application. Figure 28 shows the possibilities observed for optimizing the design of a wheel hub clamping tool developed in project FERA.

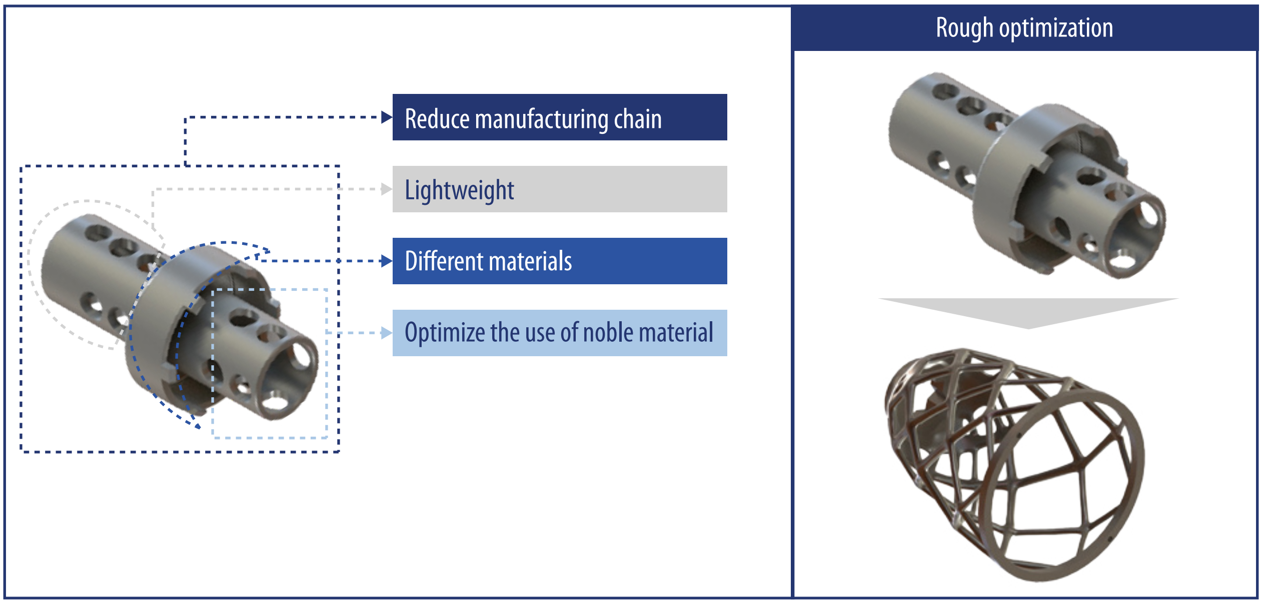


Figure 28. Possibilities for a design optimization based on the original design (Left). Rough optimized design, before the designing reconstruction and optimization loop (Right).

With the optimization defined, it is possible to move onto the design loop stage where CAD reconstruction, structural analysis, and support analysis are iterated. In this step, initially with the CAD reconstruction, the structural analysis is performed, determining the effects of the operational loads on the component. If the structural analysis step is positive, it goes on to the support analysis where the manufacturability of the component is verified, minimizing supports, or even integrating them into the part.

> “The concept was approved by the operators and the dissemination of the use of 3D printing in metal was a point that aroused curiosity in the shop floor.”
>
> *Engineer feedback*

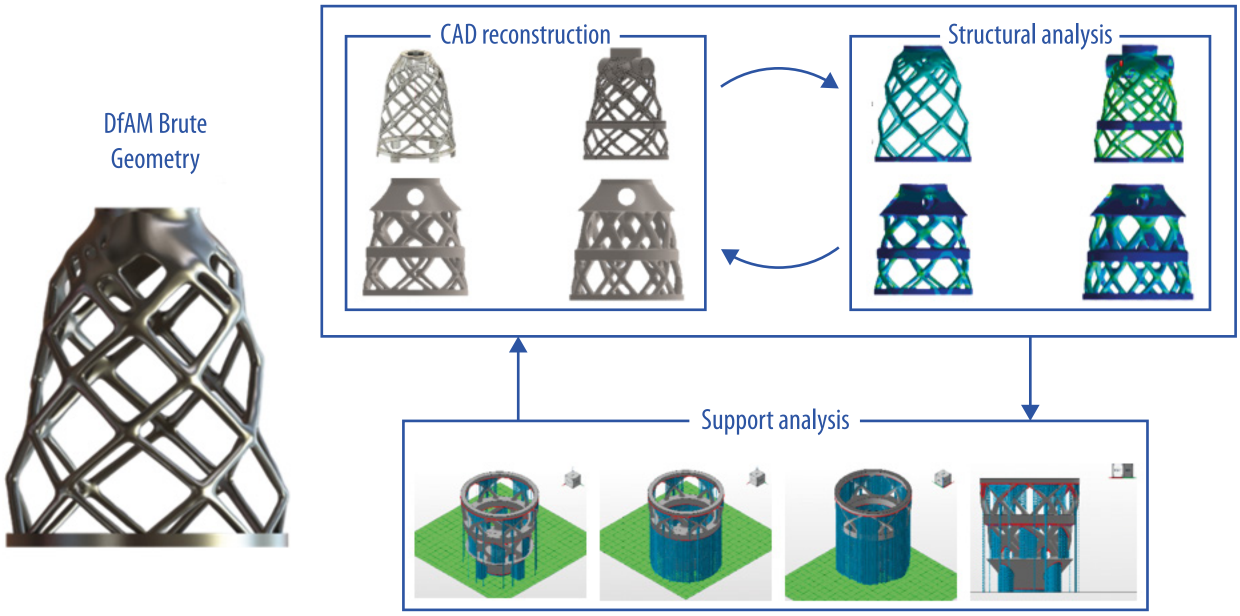


Figure 29. DfAM designing loop optimization.

> “The **3D printed** design is very **ergonomic and lighter** than the current tool.”
>
> *Operational feedback*

When any of these steps has a negative response, it is necessary to return to the previous one to analyze the changes made. During the development process of the new demonstrator in project FERA, additive manufacturing was incorporated to **reduce mass** and **increase stiffness**. Using DfAM it was possible to separate the body and the tooth bringing new possibilities such as the use of more suitable materials for each part of the component, as well as the possibility of adding safety pins to prevent the operator from any harm caused by unexpected breakage of the tool body.

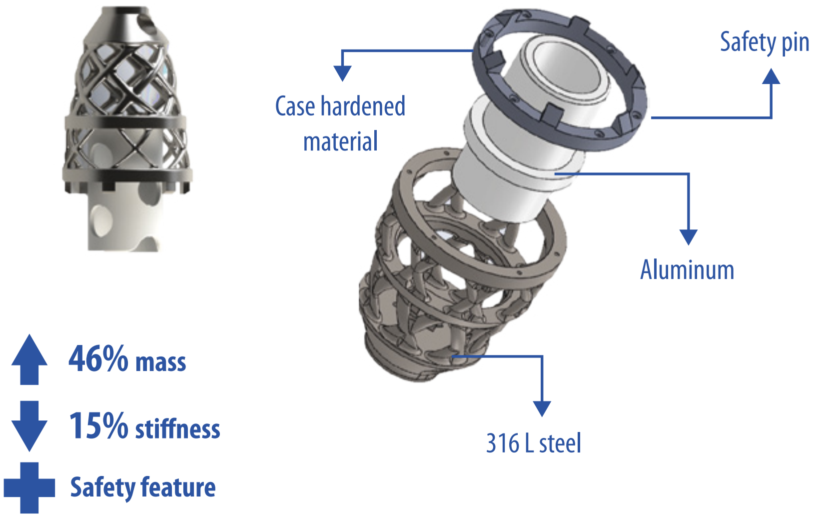
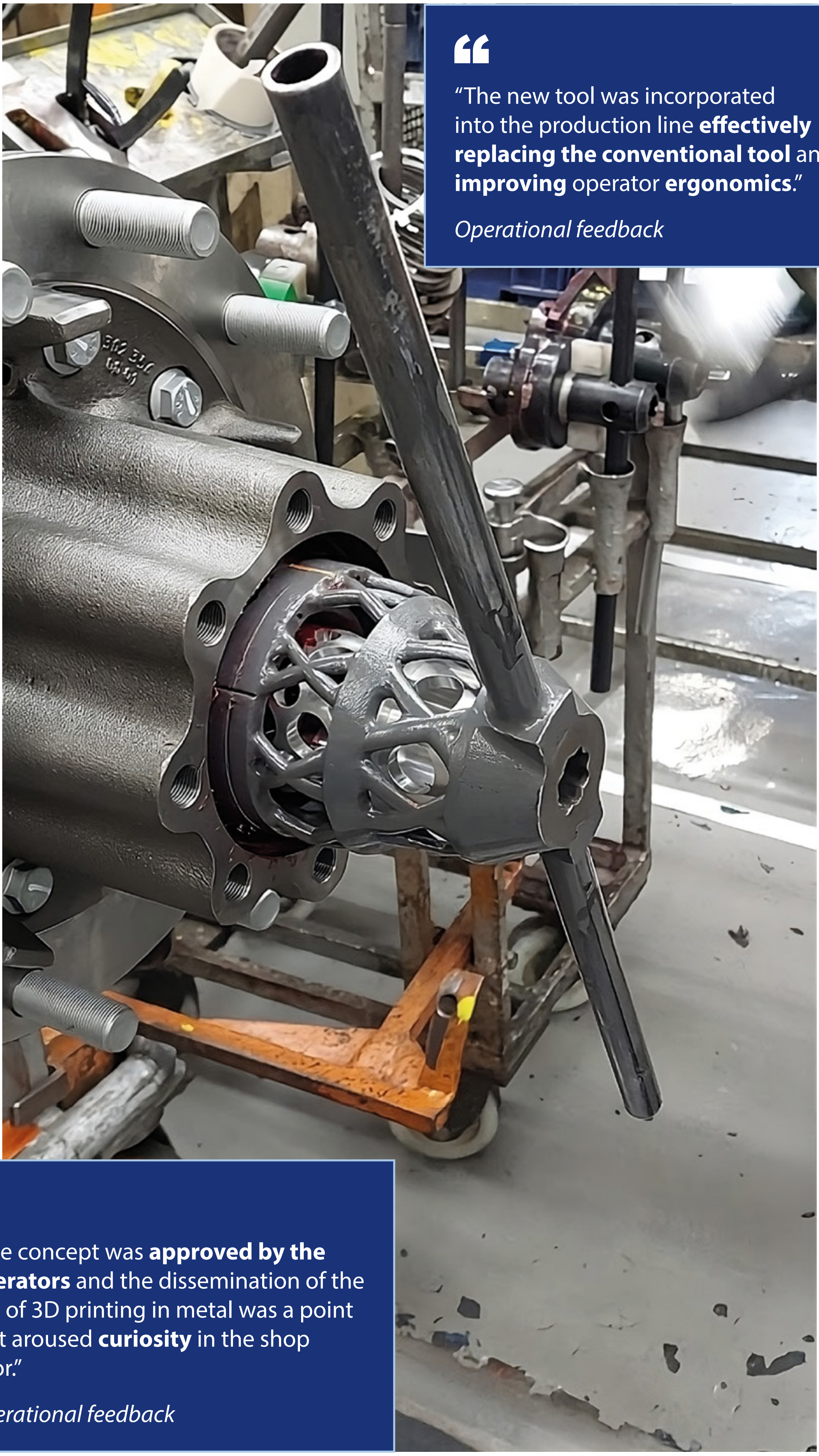


Figure 30. New design of the demonstrator after applying the DfAM concept

After manufacturing the prototype, a tryout was carried out on the shop floor of a partner company. The new tool **successfully replaced** the original tool. The new design has improved ergonomics for operators and despite its disruptive design, it was very well received by the operation. The tryout was successful, showing a **high level** of performance due to the use of **additive manufacturing** and **DfAM**, demonstrating the superiority of technology and technique when combined.



> “The new tool was incorporated into the production line **effectively replacing the conventional tool** and **improving** operator **ergonomics**.”
>
> *Operational feedback*

> “The concept was **approved by the operators** and the dissemination of the use of 3D printing in metal was a point that aroused **curiosity** in the shop floor.”
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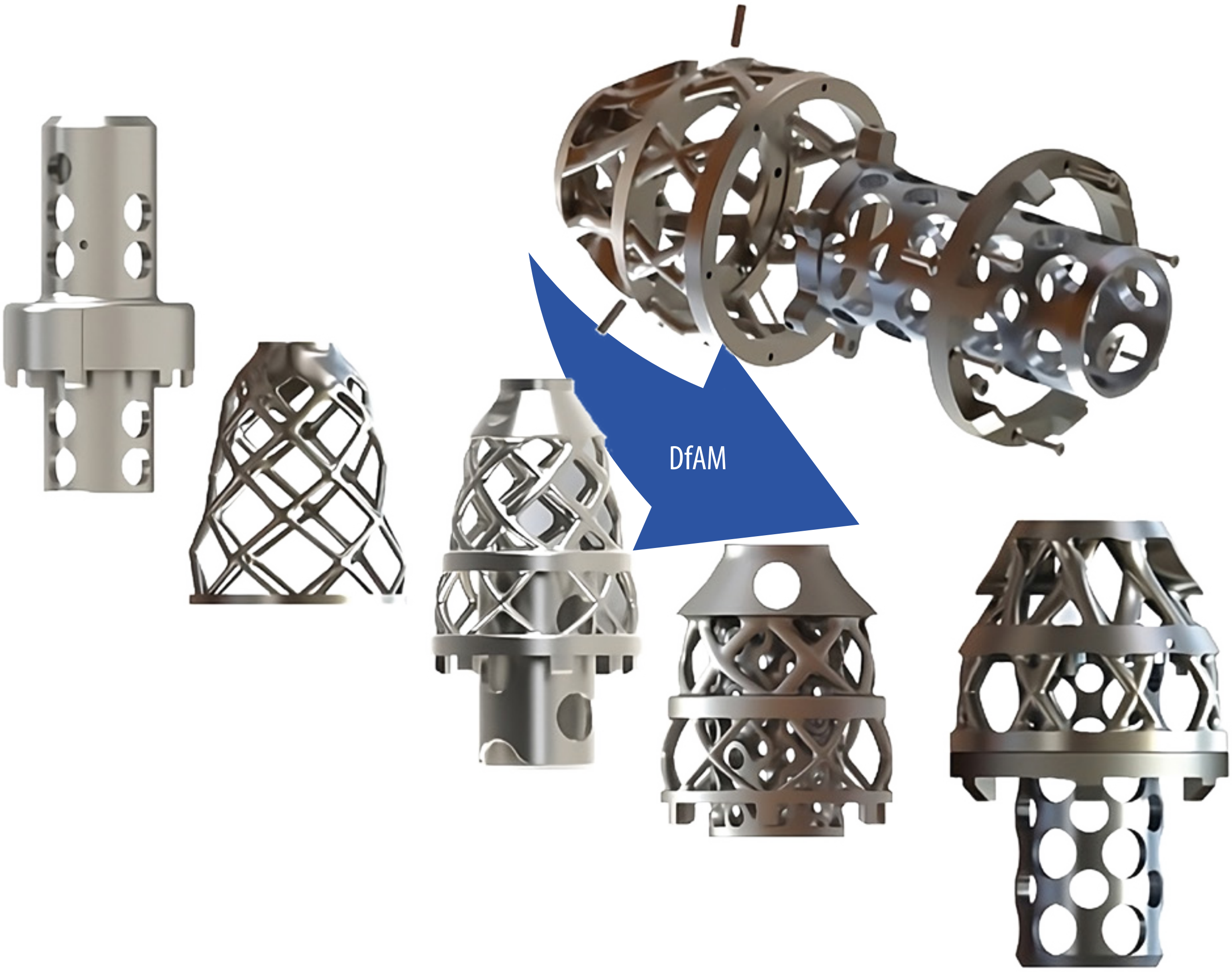
DfAM

Acknowledgment

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This textbook, featuring the main findings of the FERA project, stands as a testament to the power of collaboration, innovation, and dedication in advancing the field of additive manufacturing. The collective effort of all involved has yielded valuable knowledge and research outcomes that will undoubtedly shape the future of manufacturing in Brazil and beyond.

We would like to extend our gratitude to the ROTA 2030 program for its support and funding, which played a pivotal role in enabling this research and development initiative. This commitment to fostering technological advancements in the Brazilian automotive industry is highly commendable.

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