Study and Development of a Metal Additive Manufacturing System

Estudo e desenvolvimento de um equipamento de fabrico aditivo metálico

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"Quality means doing it right when no one is looking."
- Henry Ford

Abstract

Additive Manufacturing is a new trend in processing technology, which presents itself as an essential complement to existing traditional processes, in some cases even being considered an alternative. Capable of changing the way we perceive engineering design, it is one of the precursors of a new industrial revolution. Within this domain, metallic processing is currently on the cutting-edge of this development. Nevertheless, some challenges need to be overcome and the work here described places itself as a potential problem-solving solution and as a possible important breakthrough for process engineering.

As the current market is yet expecting new alternatives for Metal Additive Manufacturing, a project was proposed by the Portuguese industrial machinery manufacturer ADIRA, which involves two different processing technologies, LMD (Laser Metal Deposition) and SLM (Selective Laser Melting), with the objective of breaking the current boundaries and obstacles related to small processing volumes and lack of productivity, which affect the existing systems. This thesis was developed under the scope of this project, therefore being based on the development of an innovative machine, a hybrid LMD and SLM Additive Manufacturing system. An analysis of the project workflow and related activities, from process studies and preliminary concept generation up to production was made, as well as the more technical detailed project included within the proposed dissertation timeframe.

Along the thesis calendar, implementation of the LMD process was accomplished and the SLM project development was engaged as well. The project continues beyond this period and a set of activities are proposed as future work, as the plan is already established and underway, for expected completion by the end of the year of 2016.

Resumo

O Fabrico Aditivo é uma nova tendência dentro do domínio dos processos produtivos, apresentando-se como um complemento essencial aos processos tradicionais existentes, em alguns casos sendo mesmo considerado uma potencial alternativa. Capaz de alterar a forma como o design de engenharia é perspetivado, é um dos percursores de uma nova revolução industrial. Dentro deste domínio, o processamento de metais encontra-se atualmente na vanguarda deste desenvolvimento. De qualquer forma, alguns desafios precisam de ser ultrapassados e o trabalho aqui descrito posiciona-se como uma potencial solução para estas questões e um possível avanço para a engenharia de processo.

Dado que o mercado atual ainda espera novas alternativas para o Fabrico Aditivo Metálico, um projeto foi proposto pela empresa portuguesa ADIRA, envolvendo duas tecnologias de processo distintas, LMD (Laser Metal Deposition) e SLM (Selective Laser Melting), com o objetivo de quebrar as atuais fronteiras relacionadas com os baixos volumes produtivos e a falta de produtividade, as quais afetam os sistemas atualmente existentes. Esta tese foi desenvolvida no âmbito deste projeto, desta forma sendo baseada no desenvolvimento de uma máquina inovadora, um sistema de fabrico aditivo LMD e SLM híbrido. Foi realizada uma análise do fluxo de trabalho e atividades relacionadas, desde estudos de processo e geração preliminar de conceito até à produção, assim como o projeto detalhado incluído durante o período de execução da dissertação.

Durante o calendário de tese, a implementação do processo LMD foi completada e o projeto de desenvolvimento SLM foi também abordado. O projeto continua para além deste período e um conjunto de atividades estão propostas para trabalhos futuros, sendo que o plano já se encontra estabelecido e em curso, com finalização esperada no final do ano de 2016.

Acknowledgements

This work would not be possible without the contributions of some, who directly or indirectly had their role to play in this endeavour. I dedicate this work to all of those mentioned below and I sincerely hope that I can meet the expectations of everyone that contributed to this project.

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Next, I would like to express my utmost gratitude to my academic advisor, Prof. Jorge Lino, who, first of all, contributed to making this opportunity a reality. Moreover, he gave me all the necessary support and guidance throughout this endeavour, pointing me in the right direction when needed and always believing in the work that I was developing. I also thank Prof. Rui Neto for his expertise and advices, interest in this project and for following up on the developed work.

I would also like to acknowledge the entire team from the Engineering Department at ADIRA, for their support with all my technical questions. In special, I would like to thank João Paulo Santos and António Esteves for integrating me into the laser team at ADIRA and for giving me so much technical guidance for this project. Despite all my questions and difficulties, they always reserved their time to help me and to share their extensive knowledge, which gave me great motivation to keep learning and improve my work.

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I would like to thank Filipa Costa and Tiago Abreu for being by my side throughout the good and bad times, for their motivation and confidence in my abilities, even when myself would doubt them. Their contribution and interest for this thesis was undeniable, helping me overcome the obstacles along the way without ever giving up on my work.

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Acronyms

AMF – Additive Manufacturing File

BPP – Beam Parameter Product

CAD – Computer-Aided Design

CAE – Computer-Aided Engineering

CAM – Computer-Aided Manufacturing

CNC – Computer Numerical Control

DED – Directed Energy Deposition

DMLS – Direct Metal Laser Sintering

FA – Fabrico Aditivo

FEM – Finite Element Method

FGM – Functionally Graded Materials

LMD – Laser Metal Deposition

PBF – Powder Bed Fusion

PM – Powder Metallurgy

SLM – Selective Laser Melting

SLS – Selective Laser Sintering

STL - Standard Tessellation Language

List of Symbols

Θ – laser beam divergence;

M^2 – laser beam quality factor;

λ – beam wavelength;

w_0 – beam radius at the laser beam waist;

Z_R – Rayleigh length.

1. Introduction

The work here described composes the final thesis for the conclusion of the Master's Degree in Mechanical Engineering at FEUP (2015/2016), specialization in Production, Conception and Manufacturing. For this development, a report was produced focusing on the description of the produced work, which was undertaken during the second semester of the final 5th year. This thesis is therefore made under the scope of the Mechanical Engineering Department, although produced in a professional environment, with an internship status, in collaboration with the Portuguese company ADIRA.

1.1. Thesis Context

This thesis was born from an existing proposal by ADIRA, which presented the opportunity for integrating a project for the development of a new range of Additive Manufacturing equipment. Since this venture had been planned and was awaiting its start, an opening was announced for academic collaboration. Additionally, FEUP's development in the additive technology has seen an important growth and the experience gathered from a project of this nature was relevant for both, the involved Mechanical Engineering Department (DEMec) and the corresponding student.

This project came into agreement with a personal preference for this area of processing technology which meant the proposed challenge was of great individual interest. Therefore, after an initial introduction to the corresponding plan, a decision was made for starting this collaboration. This process was started between ADIRA and FEUP, allowing the intervention of a FEUP student, whose Master's thesis would be based on the work performed at ADIRA. This way, a new work experience could be provided and, on the other hand, valuable knowledge could be acquired and applied on the final degree dissertation. Further details and description of this venture are available throughout this thesis.

1.2. Proposed Project

As ADIRA, a Portuguese industrial machinery manufacturer, has great interest in innovation as a competitive advantage, ruling out new technology opportunities is not an option. Therefore, the decision regarding the entrance into a new market segment was made, more specifically, the entrance into Additive Manufacturing. As this area doesn't relate with the previously developed segments at the company, a research process was invaluable, hence the collaboration in the area of process engineering with an academic institution, such as FEUP.

This project consists on the development of two AM systems, using two different processing technologies. The first, a more short-term endeavour, is for a LMD (Laser Metal Deposition) machine (Directed Energy Deposition technology); the second production system would be based on the SLM (Selective Laser Melting) process (Powder Bed Fusion technology), with a more long-term development scope, since it presented a more distanced approach from the existing laser-cutting technology from ADIRA. Both these technological projects are described in more detail further on, in this thesis.

With process implementation and demonstration in mind, a dedicated Additive Manufacturing simulator was planned for development, integrating both processes, prior to the final machine. This way, a more progressive workflow would be made possible, with initial small-scale process validation, before final system development.

Due to the 5 months' (one semester) nature of the thesis writing process at FEUP's Mechanical Engineering course and considering the more long-term calendar for the completion of these systems at ADIRA, the full proposed project could not be included under the scope of this thesis. Therefore, the developed work inside the second semester window would be included for this dissertation and the remainder, although thoroughly described, is set to be completed during the upcoming months.

1.3. Role in ADIRA's Engineering Department

For this project, the student was integrated in ADIRA's Engineering Department, section of the company responsible for the development of the different industrial projects, as well as maintenance, equipment upgrading and long-term assistance. These projects can range from the more standard catalogue solutions for sheet metal processing, up to custom tailor-made special projects (including customized production lines and unique R&D ventures, with new technology integration and application).

As part of the Engineering team at ADIRA, the initial proposed role was for a Project Manager that would be responsible for the development process of the AM projects, collaborating with the existing laser-cutting team, which would be assigned for these new systems. This included responsibility for external company relationships in the AM domain (as the representative for these projects), as well as following up on related EU project proposals and external collaboration establishment for components supply and joint production. After establishing the AM mission at ADIRA, additional tasks were also assigned, more related with the development of the machines themselves and process investigation. Contribution to the production of the new systems ranged from process engineering, up to CAD design and machine project, with the objective of capturing knowledge of the different stages of this development. This way, the full scope of the development process was captured in a practical knowledge environment, from preliminary and conceptual studies, up until system development.

Since this project was largely based on laser technology, a visit to the Fraunhofer ILT premises in Aachen, Germany, was conducted during the development phase. This allowed for on-site training on some Additive Manufacturing processes, direct contact with existing commercial solutions and follow-up on the work developed for this project (through experimental work on ADIRA's prototype, described further on in more detail).

1.4. Report Structure

In order to fulfil the primary objective of this thesis, which is the description of the project and related work undertaken during the present semester, a specific structure was decided for this document. Starting off with the context of this project, an initial bibliographic review was produced, firstly focused on Additive Manufacturing in general and later focusing on the metallic AM processes, mainly Laser Metal Deposition and Selective Laser Melting (which were the production technologies adopted for this project).

After discussing the involved theoretical concepts, essential for a good comprehension of the matters at hand, an explanation of the current AM plan conceived by ADIRA and its contextualization is provided. This will include, later on, the specific details of both LMD and SLM systems planned for development, in each corresponding category. As a more short-term demonstration system was eventually planned for integration of these AM technologies, a specific section was also included. As this system was better comprised within this thesis time frame, more detailed machine development was conducted and included in this report. The following scheme summarizes the previously described approach:

Figure 1 - Report structure scheme, starting from the initial preliminary studies and progressing to the current system development.

2. Additive Manufacturing Technology

As a first subject, additive manufacturing technologies in general will be analysed. The main principles and common concepts to all different AM processes have been studied and the following approach (figure 2) will be followed, in order to first make a more general breakdown of these topics, later on focusing on the metallic processes (the main subject of this thesis):

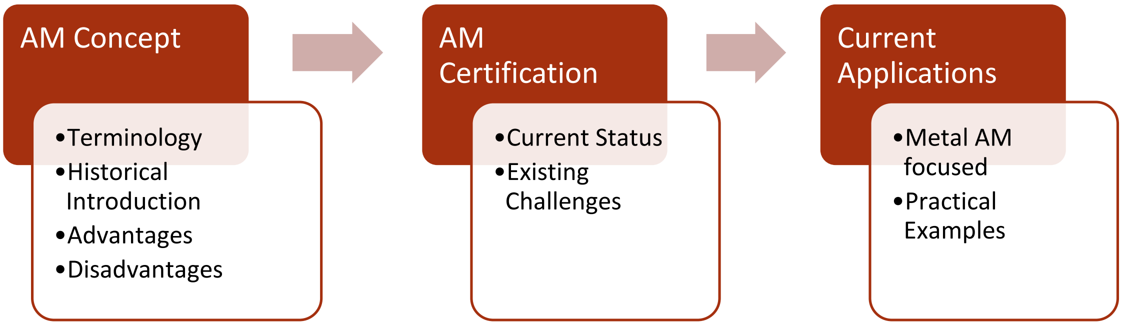


Figure 2 - Schematic of the chosen approach for the study of AM processes.

2.1. Introduction

Currently, the productive processes have an increasing role on the Mechanical Engineering domain, being the main drivers of product development for various applications. Therefore, with a progressive technological evolution of our products, it becomes necessary the development of more efficient, sustainable and complex productive processes [1].

The Additive Manufacturing domain, previously frequently named Rapid Prototyping (a somewhat reductive term, since it restricts the applications of these processes to the production of prototypes), currently places in front of the current technological revolution. These different processes differ from the more conventional methods by being based on the progressive addition of material, opposed to the subtractive methods (for example, milling, cutting and turning) or the shape changing methods (such as casting or forming) [1, 2].

Accordingly, the additive manufacturing processes follow the layer-by-layer philosophy, adding the material in a progressive way. The objective is to transform a 3D CAD model into a physical object in a more simple and direct way, not needing additional operator experience to obtain a part as close as possible to the initial idea [1].

2.2. The Additive Manufacturing Concept

Considering the great variety of processes which are included in the Additive Manufacturing domain, this concept has currently assumed great importance. This continuous technological expansion resulted in the creation of an abundant quantity of different terms, usually referring to the same concepts and, therefore, redundant. The large number of current companies influenced the adoption of this new technical nomenclature, filling countless patents in this area. In any case, the principles that drive the group of processes involved are similar and follow the same assumptions:

- The Additive Manufacturing process is started with the production of a three-dimensional solid in a virtual environment (3D CAD), which will be converted next to a specific machine language, allowing its fabrication (CAM);
- As a means of making the machine interpret the CNC numeric code, the 3D model will have its exterior surfaces configured using triangular shapes, producing the STL (standard tessellation language) file [3];
- For the layer-by-layer fabrication, the digital model must be processed once again, this time for a division in layers (slicing), along its section, originating the SLI file format. The thickness of these layers may be configurable, depending on the manufacturing equipment that will be used;
- After the slicing and processing of the digital models, the specific manufacturing process is executed, producing the intended part [1, 2].

As a way of preventing eventual distortion or shape variation, in comparison with the original model, it is possible to develop a numerical simulation in a virtual environment (CAE), increasing the accuracy of the process, by predicting its possible outcome and adjusting its parameters. Many companies also use the 3D scanning techniques available as a means of reverse engineering the part and obtain a 3D virtual model directly.

The categorization of the existing processes and the used materials are factors which will be visited along this report. Additionally, some further detailing on the software workflow is provided in its respective report section.

2.3. ASTM Terminology

Due to the vast amount of different nomenclature existent, relative to Additive Manufacturing processes, it is usual that different terms are created to serve the interests of several companies, while maintaining the same meaning. Therefore, a clear categorization is needed to correctly define and separate distinct processes.

The ASTM terminology (designation: F2792 − 12a) presents a suitable organization of AM process categories, terms and nomenclature that can include the majority of existing technology and define it accordingly. It is, therefore, a useful reference when it comes to grouping AM technologies. The existing categories are described as follows:

- **Binder jetting:** AM process that relies on a liquid bonding agent that is deposited selectively, joining powder-based material into consistent solid shapes;
- **Directed energy deposition:** process that is based on fusing material, as it is selectively placed, by melting it with focused thermal energy;
- **Material Extrusion:** additive process that consists on selective deposition of material through a nozzle or orifice;
- **Material Jetting:** selective deposition of droplets of build material for additive manufacturing;
- **Powder Bed Fusion:** process that relies on fusion of selected regions of a powder bed, using focused thermal energy;
- **Sheet Lamination:** process consisting on bonding sheet-based material, in order to form a consistent object;
- **Vat Photopolymerization:** AM process based on selective curing of a liquid photopolymer in a vat, by light-activated polymerization.

For the purpose of this project, only the relevant categories will be explored. As a result, since metal additive manufacturing will be the focus of the developed work, the more significant categories are the **directed energy deposition** processes (in which, Laser Metal Deposition is included) and **powder bed fusion** technology (comprising the Selective Laser Melting process) [4, 5].

2.4. Historical Introduction

The historical development of the AM processes involves a greater period than it would be initially expected, taking into account that it is a relatively new technological trend. The first investigations that could be included in this domain go back more than 50 years and the first commercially available equipment appeared in the 1980's. However, the AM concept appeared previously, even if it didn't have the same application as today [6].

a) First applications of the AM concept

The initial use of the concept goes back to two distinct areas: topography and photosculpture. In both these applications, the layer fabrication was used, although it wasn't known as Additive Manufacturing at the time.

When it comes to topography, in 1890, J. E. Blanther suggested the creation of topographic maps using a successive deposition of material layers, originating the shape of the pretended surface. Different materials were used along the development of this technique, starting with wax plates which were cut with the topographic contours and placed over each other. This obtained shape would be used to produce a positive and negative form of the surface, making it possible to press a paper map that would become a raised relief map.

Different methods would be developed further, based on this principle, including the selective photopolimerization of resin in a layer-by-layer fashion, similar to current stereolithography processes [7].

b) First AM processes

In 1951, O. J. Munz proposed a manufacturing process similar to actual stereolithography (SL), consisting on a selective exposure of a photographic emulsion (light sensitive substance) to the contours of an object [8].

Other primitive processes were then developed, such as a plastic fabrication technique based on a 3D polimerization of a photosensitive polymer by W. K. Swainson, in 1968. In 1971, by P. A. Ciraud, the first powder fusion process appeared, allowing the creation of solid shapes by using a laser or electron beam [9, 10]. New patents have been developed next, approaching the current processes, such as the first SLS process description by R. F. Housholder, in 1979 [7, 11].

c) Current AM processes

The first actual AM process developed was stereolithography based (SL). The first commercially available equipment was placed on the market in 1987 by the 3D Systems company. Other systems were introduced next, with progressive improvements in efficiency and productivity, as well as new processes, such as the Fused Deposition Modelling (FDM) machine by Stratasys or the Laminated Object Modelling (LOM) machine by Helisys.

By 1992, the Selective Laser Sintering (SLS) process appeared, being developed by the DTM company. New specific process followed, such as QuickCast (3D Systems and Ciba cooperation) or Modelmaker (Solidscape).

The first 3D printers were introduced in 1996, allowing low cost production of simple parts, with basic mechanical properties, mainly for prototyping. The first machine was the Genisys, by Stratasys. Afterwards, a new MIT patent (3DP – 3D Printing) was used by Z Corp to produce new, more efficient systems.

Finally, by 1997, the first metal additive manufacturing systems were made commercially available. These were introduced by AeroMet and were based on the usage of a high power laser beam for the fusion of titanium metal powder, in a process named LAM (Laser Additive Manufacturing). New alternatives were further developed, such as the DMD process (Direct Metal Deposition), used in the production or repair of metallic parts. The direct deposition process was introduced by Precision Optical Manufacturing (POM) in early 2002, based on the previously existing laser-cladding process.

High precision systems started being introduced into the AM market by 2001. At EuroMold, Concept Laser (currently a market reference) introduced their first system; EOS introduced the DirectSteel 20 system, which used 20-micron steel powder for producing parts with high precision. Further development on the EOSINT direct metal laser-sintering systems (which are currently being commercialized) were presented by 2003. The first committee for AM certification met in 2009 for the establishment of standards on testing, processes, design and terminology (matter discussed further in this report).

Since then, the progressive technological development was accelerated, originating new systems, based on a common concept, each with its own advantages and disadvantages. This great development was largely encouraged by the falling of key patents within the last decade, which made it possible for new players to develop the technology and enter the market.

The exploration of new manufacturing processes and materials is greatly encouraged, focused on the increase of productivity and efficiency in this sector. One of the main challenges which need to be overcome is the integration of the AM technology in the current productive chain. This is an area with great investment by machinery companies worldwide, that intend to integrate their systems in a mass production environment, scalable to increased product series and with high productive capability [6].

2.5. Advantages and Disadvantages

As with any production process, Additive Manufacturing presents both advantages and disadvantages, which should be considered upon deciding to proceed with this technology. For many, these processes are revolutionizing the way we perceive the development process, representing the possibility for a new industrial revolution. However, expectations must account for the existing limitations, as with any disruptive concept.

First of all, the main advantage of AM is related to its quick development capabilities. This is not exactly referring to the process itself (which can be slower than most conventional alternatives) but to the whole productive chain. With AM, there is a possibility of quickly jumping from the design to the physical part, in a single step. This allows for fast prototyping, visual 3D marketing and more importantly, for less production iterations (the final product is obtained more easily). This way, the use of different construction methods is not necessary and the build is much more simplified [3, 5].

On the other hand, increasing complexity doesn't tend to increase cost, since the precision of AM systems and the way they process the required parts, allows for complex structures, more design freedom and opening new possibilities for part production ("complexity for free, as seen on figure 3). Lightweight and functional structures are an important example of this production efficiency, being especially employed in pioneering areas such as aeronautics, for which metal AM is of the utmost relevance [3, 12].

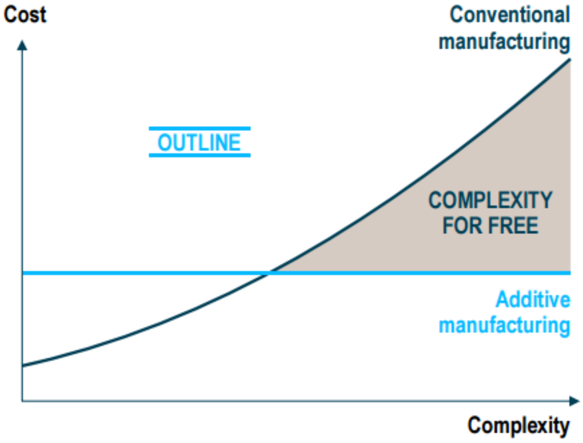


Figure 3 - "Complexity for Free", one of the key advantages of the AM technology. It doesn't contribute to an increase in costs, as it does with conventional production methods [12].

The direct approach of the AM process doesn't require specialized operators, making it even faster and easier for product placement on the market. Additionally, without the subtractive nature of conventional processes, material waste is reduced (although it can be notoriously more expensive, as explained next). Waste can be cut down by as much as 40% and about 95% of unused material may be recycled and used again (for example, powder which isn't used for a powder bed process may be filtered and reused for a new productive cycle) [13].

However, important disadvantages should be noted. Most of the time, post-processing is required for obtaining finished parts (depending on the AM process used), which affects the important process advantage of direct part manufacturing by AM. The base materials, such as metallic powder (for the processes focused on this report) are usually more expensive as well. This way, although processing costs may be cut down, material expenses tend to increase and can make this technology less competitive. Actually, recent market studies show that throughput time for an AM time can be 10 times larger and material and manufacturing costs can still be quite high (in some cases, 2 times bigger) [12, 14].

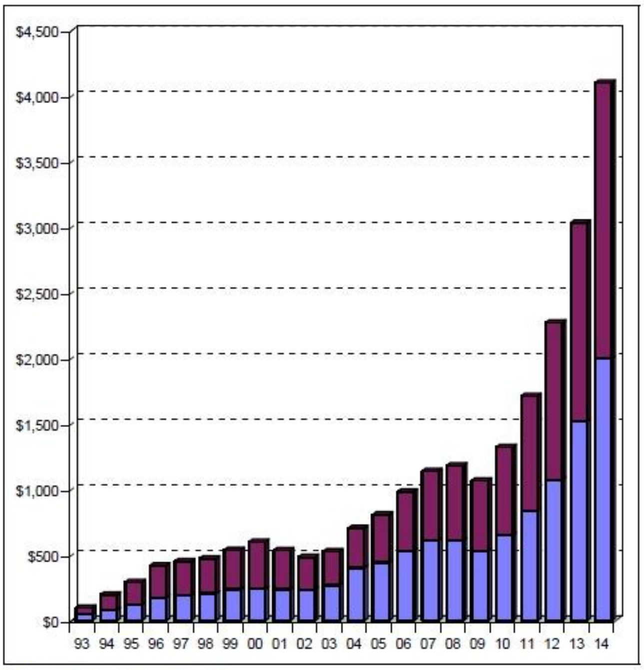
Another factor that should be considered is related to production chain integration. AM processes are still rather discontinuous, requiring manual part removal, cleaning and post-processing, which prevents economies of scale. Market regulation is also an important issue, since there is a lack of guidelines for special applications and due to the very fast development of new AM technologies, process certification is insufficient. However, as research is focused on solving these issues and margins, raw material and technology costs tend to decrease, and AM will become increasingly attractive as a productive technology [6, 12].

2.6. Market Trends

Market trends drive industry growth and investment focus from the sector players. Therefore, this factor is of the utmost importance for the several systems manufacturers, such as ADIRA, which strive to follow public demand, in order to optimize their return on investment.

a) Additive Manufacturing Industry

The Additive Manufacturing industry has seen an accelerated growth over the past five years, as the number of organizations that adopt AM products and services continues to increase (figure 4). As the AM systems selling price tends to decrease (especially for the low-cost segment), unit sales are growing. Revenues from AM products have seen a double digit increase in the last years, total product sales values around the thousands of million dollars [6].



Source: Wohlers Associates, Inc.

Figure 4 - Growth of AM products (blue) and services (purple) revenue worldwide [6].

The current trend is progressively focusing on larger series, which is becoming a reality, due to the development of faster and more efficient systems (build speed is predicted to, at least, quadruple by 2018). Current challenges still exist, mainly regarding process integration in the product chain. The usual need for post-processing and the discontinuous processing tends to prevent economies of scale. Large investments are being made to try to overcome these issues, patent on the R&D programs, funded by the EU, for example. On the other hand, certification, regulation and safety are a current concern, as well. The lack of certification guidelines for special applications (energy and offshore products, for example) tends to create obstacles on the production of components by AM processes [12].

b) Metal AM Segment

Popularity for Metal AM systems is currently growing, with an increase of about 50% from 2013 to 2014. After a short decline around 2007, mainly due to a decrease in ExOne’s Imagen dental systems sales, which was the main product on the market at the time, new Metal AM machines were developed, with more productive capability (figure 5). Metal applications are more oriented towards mechanical structural parts, since the obtained properties can be very interesting for specific applications. The remaining challenges and advantages of these processes are common to the plastic counterparts [6].

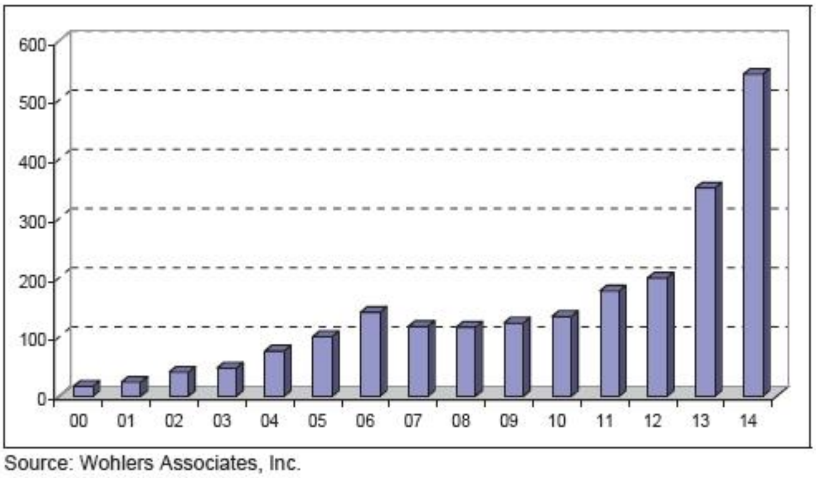


Figure 5 - Growth of Metal AM system sales.

It should be noted that the metal AM market has a higher growth rate, when compared to plastic AM, although still representing a small part of the current market (around 10% in 2012). This could be due to the more recent introduction of this technology into the market and the specific market segments, for which this technology is used (such as moulds and aerospace industry).

As build rates tend to increase and the technology availability is growing, metallic powder prices will decrease. This is of great importance for the users and manufacturers, since this material is usually very expensive, although not reflecting its production costs. Improved consumption will allow metal powder producers to sell directly to the end-user customers and make this material more accessible. It is predicted an increase in material consumption from 900 tons to 9000 by 2023.

In a parallel fashion, labour costs also tend to decrease and more automated systems are developed, with bigger production chambers, which reduce the existing product limitations and increase productivity. The entrance of larger players in the market (such as Trumpf or DMG) with high budget R&D and increased investment will further drive the costs down [12].

2.7. AM Certification and Regulation

Additive Manufacturing certification is a recurring issue, since this recent technology doesn’t have any common norms to regulate the involved production processes and produced components. This lack of guidelines is an important factor to be considered, as it doesn’t allow AM to be presented as a complete alternative to conventional processes. Industrial implementation is not a possibility until dedicated standards are released, which should be able to facilitate quality management, part predictability and reproducibility. Nevertheless, current implementation of AM processes is important in crucial areas such as aerospace or the energy sector, therefore standardization can help increase its uses in today's industry.

For solving this issue, some projects were started, such as the EU SASAM (Support Action for Standardisation in Additive Manufacturing) consortium with over 100 industrial stakeholders, which attempts to manage the standardization process of this technological area, by establishing cooperating efforts between ASTM F42, CEN/TC 438 and ISO TC261 (the corresponding American, European and International norms for AM). In any case, some needs from current industry players are still awaiting fulfilment, such as:

- **Design:** standardization of design procedures of AM-produced parts;
- **Specific industrial needs:** restrictions that are applied to different industrial sectors that have implemented AM technology;
- **Part quality:** standard regulations for control of parts obtained for different industrial sectors;
- **Safety regulations:** material handling and processing must be regulated for the variety of AM processes.

Some existing standards from other sectors may be indirectly related to AM processes, such as powder metallurgy ISO norms. However, these were not developed with AM in mind. Furthermore, specific standardization can support the possibilities for certification and approval of AM products for medical and aviation applications, which present strict safety policies that must be respected. This way, projects such as SASAM are of great importance, serving as a foundation to the various technological developments, which are being, in great part, funded by the EU itself. Standardisation is converging on a single set of AM standards for use throughout the world, with a common organization and roadmap [15].

2.8. Current Applications

Additive Manufacturing is an increasingly widespread technology, being applicable to more and more areas of interest for today's society. Commonly known as Rapid Prototyping, since its first uses were centred on this matter, it is currently being considered in a more versatile approach, including mass production of special parts with certain requirements which can only be fulfilled by AM. Some applications are described next, mainly focused on metallic processing technologies.

a) Engineering (design and manufacturing process)

As previously mentioned, design freedom is one of the most important advantages of the AM processes, allowing for more product possibilities, which is of great use for rapid prototyping. An interesting example of the freedom of design is the production of a lightweight optimized frame for the EDAG “Light Cocoon” concept car, produced by using a combination of Additive and Subtractive Manufacturing processes (figure 6) [16].

For engineering purposes, fast prototyping capabilities makes it easier for fit testing (concluding about a part inclusion in an assembly with the production of jigs, fixtures, templates and other guides), functional testing (some AM processes produce functional and ready to use parts), as well as form testing (evaluation of the design, visual marketing and conclude about the manufacturability of a certain component). Some traditional processes used for prototyping, such as investment casting may be aided by AM. For example, patterns for the mentioned process are expensive and time consuming to produce. Since there are suitable AM materials that allow the production of these patterns, the process may be accelerated and productivity increased, making AM a suitable complement to conventional processing [6].

Figure 6 - Lightweight frame consisting of steel profiles as connecting elements and AM space frame nodes, made with the ConceptLaser PBF AM process (left) and the EDAG concept car (right). Nodes and profiles can be adapted to new geometries and load requirements easily, with the use of AM technology [16].

Another important application for engineering is the implementation of Rapid Manufacturing. Without the need for tooling and with the capability of producing near-net shape products, the industry is considering the AM processes for producing components in a more direct way, accelerating the production process and reducing costs for special and custom parts. The products can vary from complex parts for assembly in a functional mechanical system, to jewellery, modification of existing shapes (design optimization for lightweight parts, for example) or customized consumer goods (in various items, such as personalized headphones to running sneakers) [17-19].

b) Industry

One of the strongest applications and earliest drivers for the AM processes is rapid tooling. For several manufacturing process, such as injection moulding or investment casting, AM can produce the necessary tools in different materials, ultimately making it possible to obtain the final shapes in a more direct approach (although accuracy and durability should be evaluated). A reduced set of processing stages will make it possible to reduce both costs and time consumption.

Especially complex mould inserts or patterns for injection moulding may be produced by SLS or SLM processing (figure 7), with an increasing availability of different materials and metallic alloys which enhance the obtainable mechanical properties for long run production processes. Mould production lead time may be reduced from 10 to 25% and productivity due to enhanced thermic performance may increase by 20 to 30% for both metallic and plastic parts. [20]

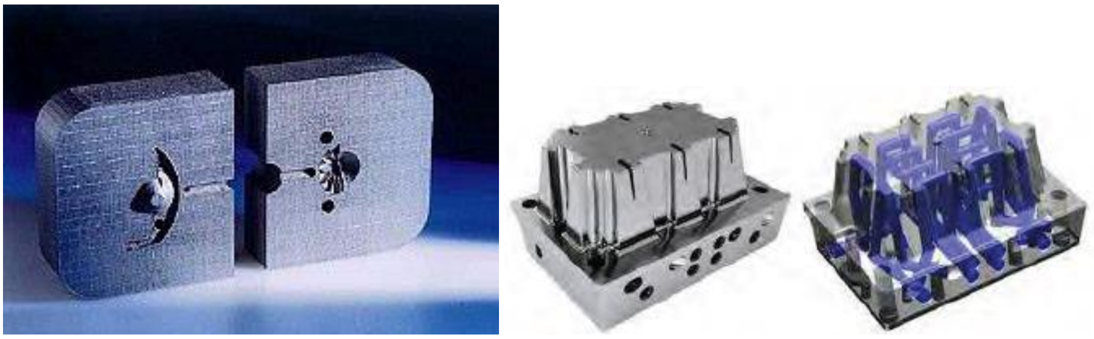


Figure 7 – From left to right: mould insert produced by SLM (courtesy of MCP-HEK Tooling GmbH, Germany) [17]; moulding tool insert with conformal cooling (CAD rendering on the right), by HRSflow [6].

Additionally, new features, such as conformal cooling (as seen on figure 7) and functionally graded materials (another topic discussed later on) may be used for the moulding process. Part and tool repair operations are also very important, being an evident advantage of DED (Directed Energy Deposition) processes, such as LMD, reducing operating costs by reusing existing structures [6, 17].

c) Medical

As great complexity can be achieved with AM, this technology is being used as an important contribution to the medical sector, being an alternative to the widely used investment casting. Surgeons are able to rapidly reconstruct selected patient body structures from CT or NMR data for study and planning of necessary interventions and medical procedures, both reducing the risk to the patient, as well as making the process easier for the doctor. Dental reconstruction, tumour removal, bone healing and repair are just some of the possible applications for these methods.

A common application for Metal AM is the fabrication of prosthetics, guaranteeing a correct fit to the patient's body, with high capability for design optimization and with low material waste (figure 8). Available biocompatible materials for metal AM, such as titanium or cobalt-chrome alloys, make it possible to implement such solutions. Surface quality is a factor of great importance and although investment casting may present a more uniform result, porosity can be an advantage when it comes to adhesion between the prosthetics and the bone itself [13].

Figure 8 - Knee implant produced with a Co-Cr-Mo alloy [13].

d) Aerospace

The transportation sector is becoming more and more interested in AM for the production of several complex components. However, the most profitable domain is the aerospace industry, which has contributed to a very important growth of additive technologies, especially for metals. Aerospace parts present high added value and usually require complex and lightweight shapes with high mechanical and thermal resistant materials (which is currently possible to achieve with metal AM).

GE Aviation is an important example of the usage of additive technologies for component mass production, producing more than 30.000 fuel nozzles per year for the new LEAP engine (figure 9). This component design was overhauled and this was only made possible due to the application of AM processes. The different separate parts were combined into one and the joining operations were removed from the production chain. As a complement, the nozzle is 25% lighter, more durable than its previous version and more efficient [6].

Part repair is once again an important application to consider for aerospace and the ability to produce components in one single stage with near-net shaping is critical to make this technology highly competitive.

Figure 9 - Fuel nozzle for the LEAP engine (GE Aviation) [6].

3. Metal AM Processes

Additive Manufacturing is currently a very important area of development and the more specific Metal AM segment is even more significant. In fact, this sector has seen a growth of over 75% by 2013, in comparison with a 34.9% evolution of the whole AM industry. It is safe to say that Metal AM has progressed more in 10 years than the traditional plastic processes did in 25 and this is possible due to the great industrial interest in this technology, which constantly provides new alternatives and developments [21].

The main industries which are driving the evolution of the Metal AM processes are the automotive, medical and aerospace sectors. Industrial acceptance of the produced parts for important structural applications is slowly becoming a reality, since the resulting mechanical properties are very interesting. However, process reliability and repeatability are also reasons of concern that should be considered [22].

On this project, two types of Metal AM processes are involved and further explained in detail: LMD and SLM. These were the focus of the developments at ADIRA and have been studied throughout the established activities. Accordingly, the following approach (figure 10) will be followed, regarding the more specific analysis of Metal AM processes:

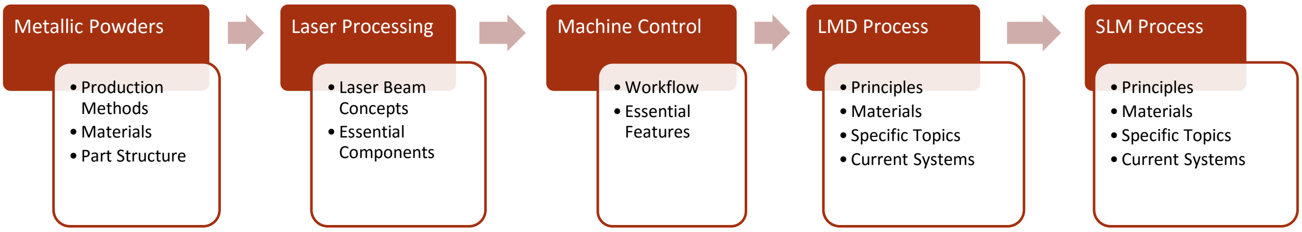


Figure 10 – The followed workflow for a specific Metal AM analysis.

3.1. Metallic Powders

The basic material, common to the studied processes is metallic powder. Several suppliers, such as Sandvik (Sweden), LPW (United Kingdom) or Oerlikon (Switzerland) currently have regular production of these materials for special applications and specially focused for AM processes. Different metal types are available, allowing a vast amount of different applications, and a high variety of grain sizes are offered. Therefore, the choice of metallic powder is not always easy and the existing possibilities are indeed vast.

a) Production process

The majority of AM systems require metal powder that presents a spherical shape, uniformity in size and density. Blown powder (DED) systems are less demanding when it comes to uniform and spherical shape, since the injection of powder to the energy source is easier. For powder bed systems, the case is different, since these systems demand a uniform, dense and fully flat layer of powder before melting. Any significant variation in powder size and shape can be potentially significant for the success of the process. Additionally, for these systems, powder flowability is of great importance, since increased flow capability makes powder dispersion through the build area much easier [6].

Metal powder for AM applications is mainly produced by the atomisation process. The traditional method consists on feeding metal, in a form of a bar or wire, into a heat source, rising its temperature beyond its melting point. The melting occurs inside a protected environment (inert atmosphere or vacuum) and the heat source can be provided by plasma torches or an induction system. Final temperature should be high enough, in order to avoid premature solidification. The molten metal is then dropped through a vertical chamber, solidifying in a spherical form (figure 11). This process can achieve production rates of up to 400 kg/min and produce a vast variety of metallic materials [6, 20].

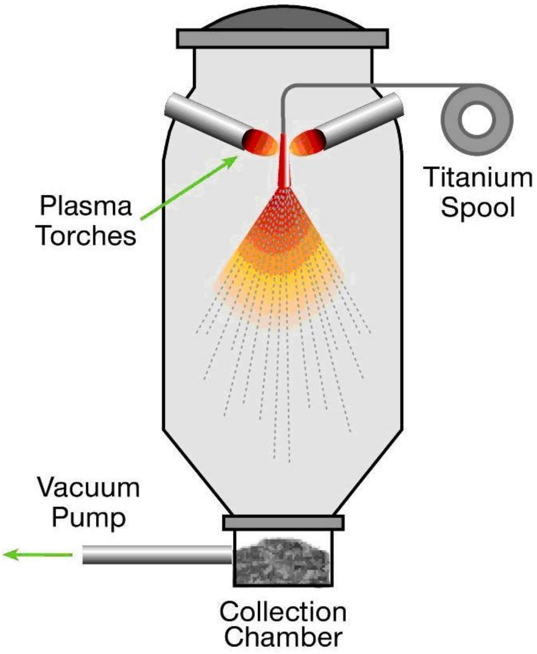


Figure 11 - Plasma atomisation process for producing metallic powder [23].

In order to better control the size and shape of the resulting particles, it is possible to inject gas into the melting area (this process is therefore called gas atomization, as seen on figure 12).

Different types of gas can be used, ranging from normal air or nitrogen to inert gases (which prevent possible oxidation and especially relevant for oxidation sensitive metals), such as helium or argon. Horizontal spraying of the particles can also be used with lower melting temperatures.

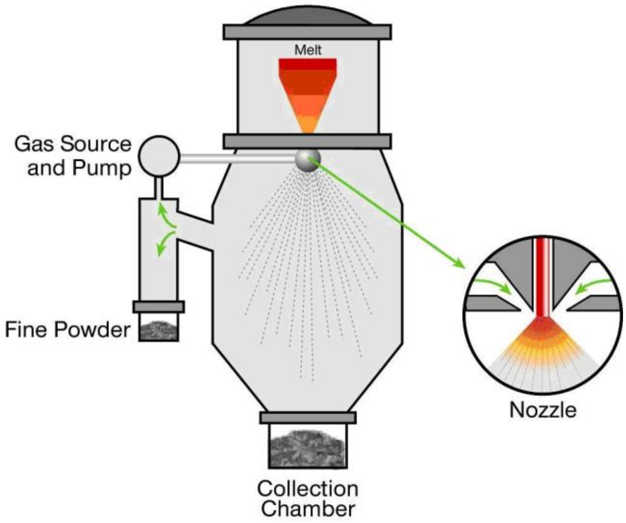


Figure 12 - The more common gas atomisation method [23].

Another alternative is the use of water injection, causing a fast solidification of the molten metal. Water atomisation is commonly used on the powder metal industry, allowing for a faster process and reduced costs, although it should only be used with metals whose melting temperature is under 1600 °C and not sensitive to oxidation. Nevertheless, the resulting particles are irregular and therefore not usually desirable for AM operations (comparison on figure 13) [6, 20].

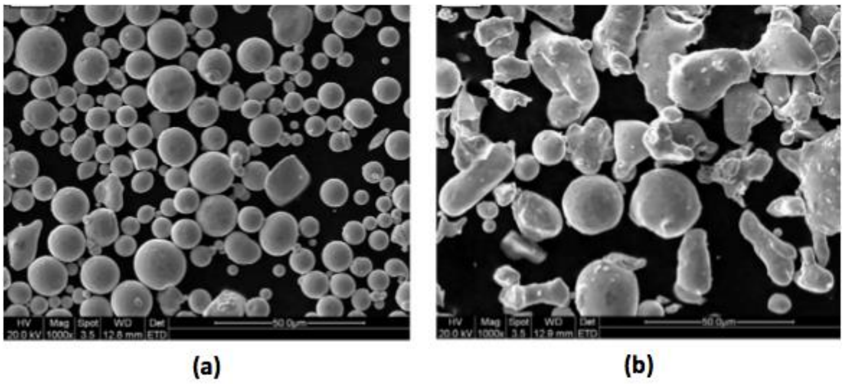


Figure 13 – Powder grain shape differences between gas atomisation (a) and water atomisation (b) [20].

Powder atomisation can produce a vast range of sizes for powder metal. Larger particles, above 100 µm may be used on DED systems; medium particles on the range of 45 to 100 µm are suitable for EBM machines; smaller particle size on the range of 30 to 45 µm are usually recommended for powder bed systems (although smaller grain sizes may be used, particles below 10 or 20 micron may negatively affect powder flowability [24]). Other less conventional methods, such as centrifugal atomisation (Plookphol et al., 2011), chemical vapour deposition (CVD, by Jovic et al., 2006) and mechanical milling (briefly described later on) are also currently used [25].

Important defects that should be considered can be: particles not fully dense (due to trapped gas from the atomisation process), satellite powder structures (formed by bonding of different liquid droplets during dispersion) or joining between neighbouring particles (partially melted powder can cause localized bonding). Abnormal particle size can be avoided by using sieving equipment, which filters the undesired particles. This type of solution is also implemented on current SLM installations, as referred on the corresponding section of this report.

Metal powder production costs are an important factor with great influence on the current AM market growth (figure 14). The associated costs are essentially related to the powder size distribution, type of used atomisation (gas atomisation with inert gas being the most expensive method) and the AM process to be used. Related to this last cost driver, a powder bed system will use, on average, less than 20% of the supplied powder in part production and doesn't allow the use of coarser grains, unlike a DED machine which may be able use water atomised powder.

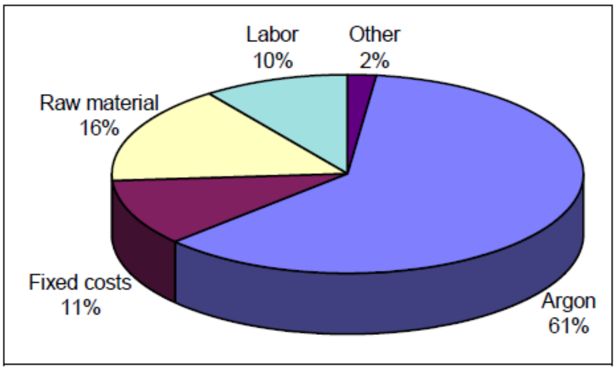


Figure 14 - Gas atomisation cost breakdown, by Robert Wilson [6].

On the other hand, unlike polymer-based systems, there is an increased freedom when it comes to powder selection, since the users can choose from different suppliers, without the need to buy directly from the system manufacturer. This presents better cost control for the user, since powder expenses are one of the main factors that influence AM part production costs. Nevertheless, some machine manufacturers may emphasize that technical support may not be available if a problem should arise with a non-recommended powder [6].

Additionally, some environmental concerns have been discussed regarding the metal processing industry, therefore recyclability is a very important property to be considered. With this in mind, novel methods for producing metallic powder are being considered, one of them being the powder production from recycling machining chips, by using mechanical milling (Canakci et al., 2012). The metallic chips from a regular milling operation can have their size reduced by using a roller crusher (figure 15) and posterior ball milling (by using grinding balls inside rotating grinding bowls). This method has been proven as a potential alternative to conventional atomisation, as finer particles are obtained with longer ball milling periods (figure 16) [25].

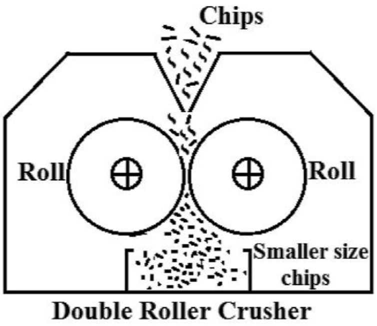


Figure 15 - Roller crusher method for reducing milling chips size [25].

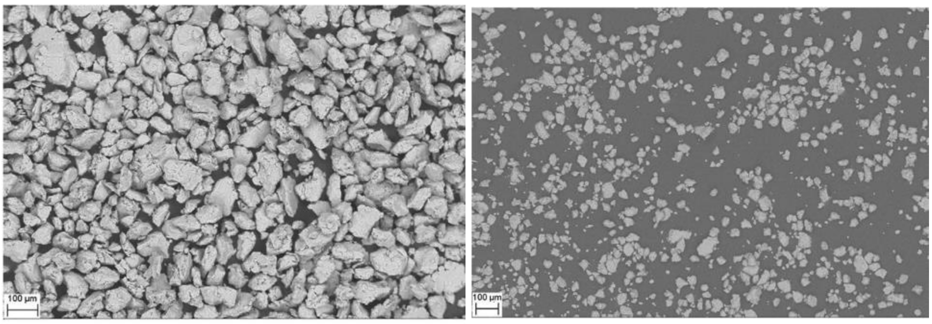


Figure 16 - Comparison between particles obtained after 5h ball milling periods (left) and 10h processing time (right). Same size scale was used [25].

Other interesting process is the liquid-solid method (LS method, by Cheng et al., 2016), in which irregular metallic particles (which need to be rounded) are scattered within powder material with low surface energy (such as graphite powder). After heating the mixture beyond the liquidus temperature of the metallic material, under an inert atmosphere, the liquid-solid tension on the metal surface would make it possible to obtain isolated spherical metal particles that are later on collected by filtering the mixture (figure 17). By taking advantage of the low wettability of metal liquids on another material (which depends on the base metal that needs to be processed), it is possible to obtain round particles (as seen on figure 18), in a rather inexpensive way [26].

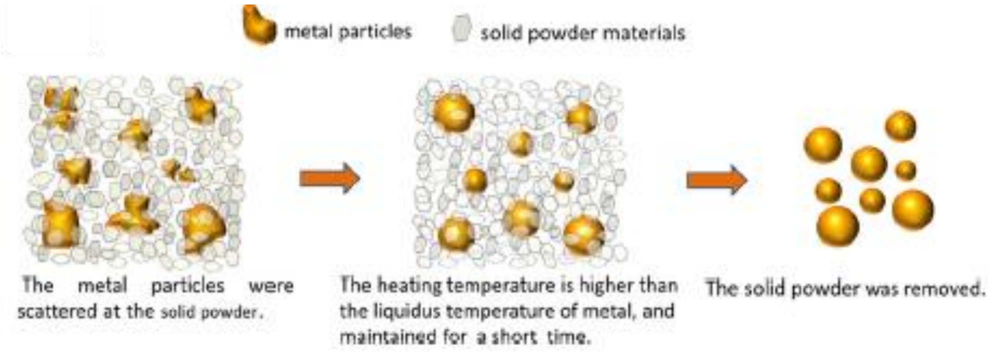


Figure 17 - Scheme for the working principle of the LS method [26].

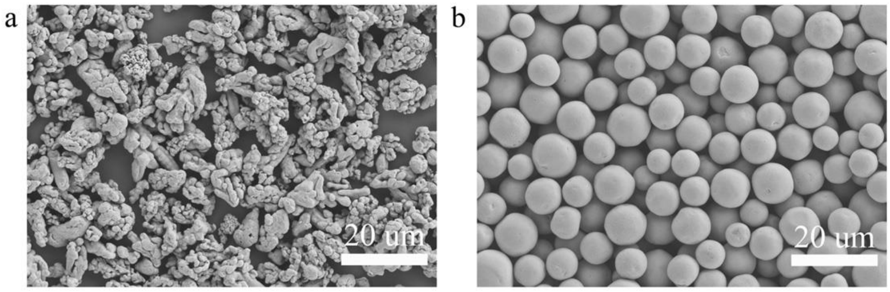


Figure 18 - Raw Cu material (a) and its resulting rounded powder (b) after using graphite for the mixture [26].

b) Available materials

Up until now, only a limited number of metallic alloys have been officially supported for AM processes. However, the amount of different materials has been increased throughout the last years and the current range of possibilities goes from more conventional alloys (such as tool steels and stainless steels) to the so called super alloys (such as Inconel or Stellite):

- **Titanium alloys:** different types of titanium based alloys are available, being the Ti-6Al-4V the most extensively investigated and used. This type of material presents high service temperature capability (up to 1600 °C), great corrosion resistance and low density combined with high mechanical strength. Common applications (figure 19) include the aerospace industry, medical implant production and other special sports or transportation solutions;

Figure 19 - Bladed disk (left, Sciaky Inc.) and a hip implant (right, SLM Solutions GmbH) made from titanium alloys [27, 28].

- **Aluminium alloys:** widely used alloys along with steel, allowing low density structures with complex geometries (figure 20). However, with a high specific heat, it usually requires large amounts of energy until melting and is prone to oxidation during processing. It is vastly used for the production of lightweight aerospace components and common produced alloys include the Al-Si-Mg alloy 6061. It should be noted that aluminium powder is classified as flammable and combustible, being necessary additional care when handling this material, preventing electrostatic charges, humidity and contact with other flammable materials [29];

Figure 20 - Aluminium bladed disk for the naval industry [13].

- **Nickel alloys:** less common alloys (usually defined as super alloys) with excellent corrosion resistance, mechanical strength and fatigue capability at high temperatures. Aerospace engine parts (figure 21) which may be required to work under stressing high temperature conditions are usually produced with these materials, as well as energy production components. Nickel chromium alloys, also known as Inconel are usually used (mainly IN625 and IN718);

Figure 21 - Rotor made from Nickel-based IN718 (Morris Technologies, USA) [28].

- **Cobalt-chrome alloys:** another type of super alloys which are commonly used for metal AM processes (figure 22). In order to keep its original properties, vacuum processing may be used (such as the Electron Beam Melting process), preventing alloy contamination by the atmospheric gases. Medical implants may be produced with these materials, since they allow great wear resistance, great temperature capability, high rigidity and very good finishing. This material is also an important alternative for aeronautical applications (turbine components) or plastic injection tools (complex geometries with conformal cooling structures). Most common alloys are of the Stellite® type, with tungsten, molybdenum and carbon additions;

Figure 22 - Knee implant made by DMLS, using bio-compatible Co-Cr alloy (Stryker Orthopaedics) [28].

- **Steel:** iron-based alloys are some of the easiest processing materials for AM processes. Stainless steel is vastly used, presenting great corrosion resistance and ideal mechanical properties for most applications, from functional prototypes to mass production of high strength structures. Most common stainless steel products include the 316 and 316L alloys, 420 and 347 steel. Tool steels may also be used for more demanding applications, such as the H13 steel for hot working conditions;
- **Other materials:** new alternatives are available for metal AM processing, such as special refractory materials. Refractory tantalum-tungsten alloys may be used on metal AM processes for titanium bone implants surface deposition, due to the high biocompatibility of this material (although being quite difficult to process since it presents a melting temperature of over 3000 °C). Sintering of alumina powders may also be considered for high temperature resistance of the resulting parts. [13, 30, 31].

c) Functionally Graded Materials

Material selection is a critical step in every mechanical project, since it will determine the obtainable capability of the involved part or structure to withstand its applied load. However, high load situations usually limit the material choice to a selection of high strength alloys, available to design engineers. In order to increase this selection, alloy combination is a greatly researched topic, allowing for further fine tuning the end product to the needs of a certain application, giving new options for mechanical design. This is where functionally graded materials (FGM) come in.

FGMs are a specific type of materials that present a gradual variation of their composition and material structure along their volume. These materials eliminate the sharp interfaces existent in traditional composite materials (where failure is usually initiated) and instead implement a gradual and smooth transition between constituents. This concept appeared in the mid-1980s with the necessity to develop heat resistant materials for the aerospace industry and has become a more recurrent solution for other sectors as the conventional fabrication techniques (such as centrifugal casting) are being conveniently replaced by more disruptive processes, such as AM. This was achieved with different powder bed processes, such as SLS (Erdal et al., 2010, were able to produce a controlled variation of mechanical properties by varying energy density level), or DED, such as the LENS process (Balla et al., 2009, fabricated FGMs composed of Titanium and TiO_2) [32, 33]. The usage of DED processes for FGMs is especially interesting, considering the capability of depositing different metallic powders simultaneously (when multiple powder storage units are available) or in alternate layers (wafer-type structures), both variants present on figure 23 [34, 35].

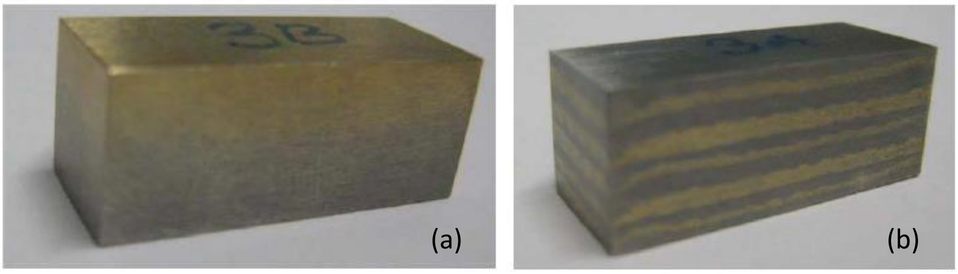


Figure 23 – Continuous FGM material without a defined interface (a) and an alternate wafer structure (b) [34].

The evaluation of the mechanical properties of a FGM usually requires a dedicated testing procedure for each combination, due to the unique nature of the resulting material. Nevertheless, resulting properties of the new structures tend to be placed between the individual characteristics of each individual constituent, allowing for a gradual optimization of the final properties, by changing the proportion for each base material. Wafer structures tend to have a more localized behaviour, maintaining each constituents' properties within each layer, therefore presenting a less homogeneous distribution [34].

d) Metallic microstructure

Common manufacturing processes for metallic alloys include casting, ingot forging/milling (wrought alloys), powder metallurgy (PM metal alloys) and more recently, direct manufacturing through electron beam melting (EBM), direct deposition (such as the LMD process) or powder bed laser melting (SLM processing). These new additive processing techniques bring new realities when concerning metallic microstructure.

Wrought alloys present advantages when it comes to fine tuning material properties, since these can be thermal and mechanically treated (cold or hot working as well as further heat treatment) until reaching final shape (thus tailoring the mechanical properties). PM and cast products are fabricated with the final shape in mind, without the possibility of further heat treatment or processing, however being able to obtain net shape products more directly. PM products should be specifically monitored when it comes to porosity, which is directly dependent of powder compaction and has great influence in the material fatigue and fracture properties. [36]

When it comes to AM processes, due to their layer-by-layer process nature, complex temperature profiles are established throughout part fabrication, leading to intricate microstructural configurations for the produced parts. These profiles generate alternated melting and solidifying stages, repeated phase transformations and thermal cycles depending on the amount of passes between different layers and part size. Cooling rates are also relatively high for the different additive processes (for example, 10^3 to 10^4 K/s for the Optomec LENS process and 10^4 K/s for SLM) and the occurring heat flow generally results in columnar microstructures (directional cooling), as presented in figure 24.

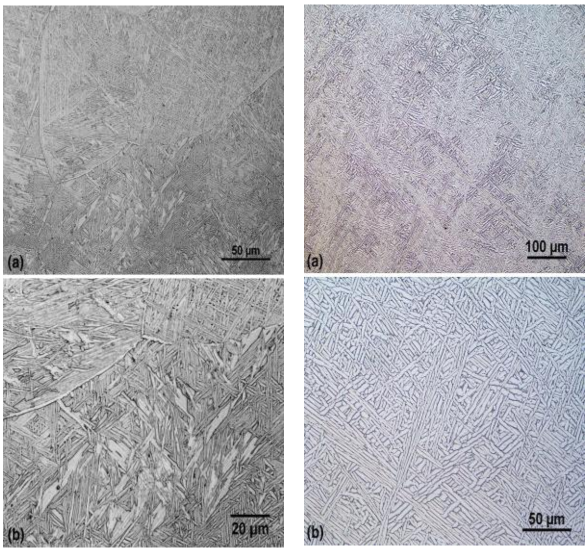


Figure 24 – Microstructure for a titanium alloy produced from laser processed blown metallic powder (left) and wire-fed EBM processing (right). Bigger grain size may be verified in wire-fed processes due to the larger melt pool, which leads to slower cooling rates and increased grain growth [30].

The mentioned characteristics of the thermal variation for the AM processes greatly influence the resulting microstructures of the deposited materials. Directional grain growth in the direction of heat propagation, tends to originate high material anisotropy, with important differences between successive deposition layers. Additionally, micro-porosity due to gas entrapment and lack of fusion are also present, especially for powder bed processes, such as SLM. Microstructure and layer dimensions may also be controlled by tuning the used powder size distribution, as well as additional process parameters, such as beam energy, scan rate or scan pattern sequence. These different properties may be verified within narrow build volumes, alternating between layers as the parameters are changed (figure 25) [30, 36].

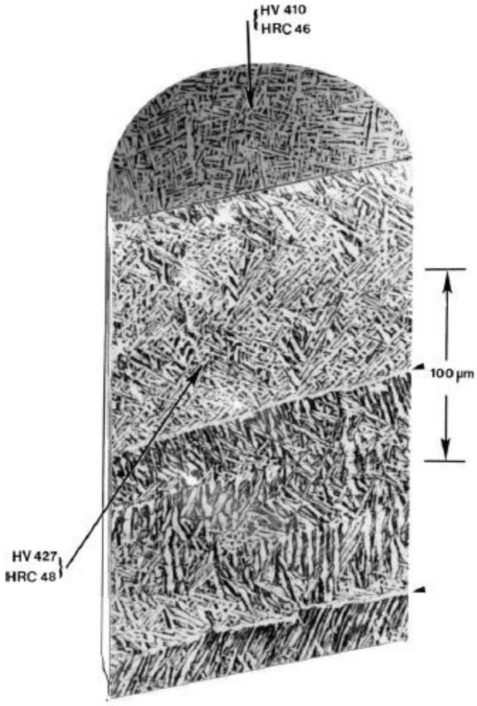


Figure 25 - Enhanced section views for a cylindrical Ti-6Al-4V build with the average Vickers (HV) and Rockwell (HRC) hardness values (build direction from bottom to top) [36].

When comparing the microstructure of powder processing with the wire-feeding technique, a finer structure is found on the first case, since larger melt pool and slower cooling rates are associated with the second case. Fatigue resistance may be reduced by inclusion of atmospheric gases during the process, which tend to increase part porosity. Therefore, different system manufacturers tend to apply inert atmospheres or even vacuum during the process, in order to reduce this influence [30].

e) Sintering vs. Full melting

Different metallic powder binding mechanisms are currently available and may be implemented for metal AM operations. Sintering and full melting are the most common on current AM processes, being both applicable to the SLM process (for LMD, only full melting is possible, hence the superior laser power systems).

The sintering process (figure 26) has been in use on current PBF AM systems longer than full melting and is based on the fusion of the powder particles without melting (in their "solid state"). The temperatures for sintering are situated between the material melting temperature and half its value. The applied temperature by the laser system will reduce the total free energy of the powder particles (as the surface area decreases when particles fuse at high temperatures, the surface energy is also reduced) and cause them to fuse. The use of external pressure, higher temperatures or longer sintering times tend to reduce porosity and enhance the sintering process. Nevertheless, the particles do not fully melt and they will connect by localized fusion on their surface, therefore some pores can continue to exist between sintered particles.

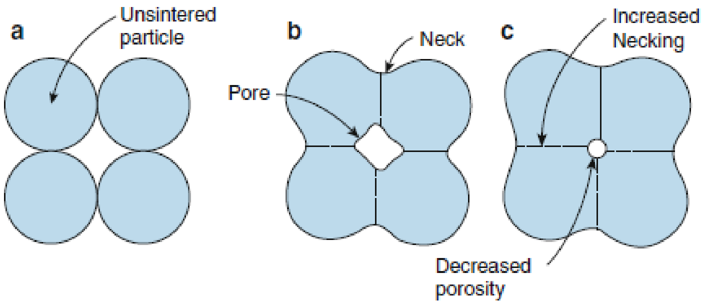


Figure 26 - Sintering process from the unsintered particles (a) to the generation of necking (b) and the final sintered structure (c) [3].

Coated powder particles may be used to help with the sintering process (for example, polymer-coated metal particles), by reducing the necessary thermal energy for the sintering process (indirect processing of metal powder). The coating will be responsible for the particle binding and will sinter with less heat, while the core material will serve the purpose of providing the necessary part mechanical strength and remains largely unaffected.

Resulting green parts from indirect processing tend to present high porosity, therefore they are subsequently processed in a heating furnace for vaporizing the polymer binder (debinding phase) and sinter the metallic substrate. Remaining pores may be filled with an infiltration of a lower melting point metal or additional sintering (by increasing the temperature), in order to solve the porosity issue.

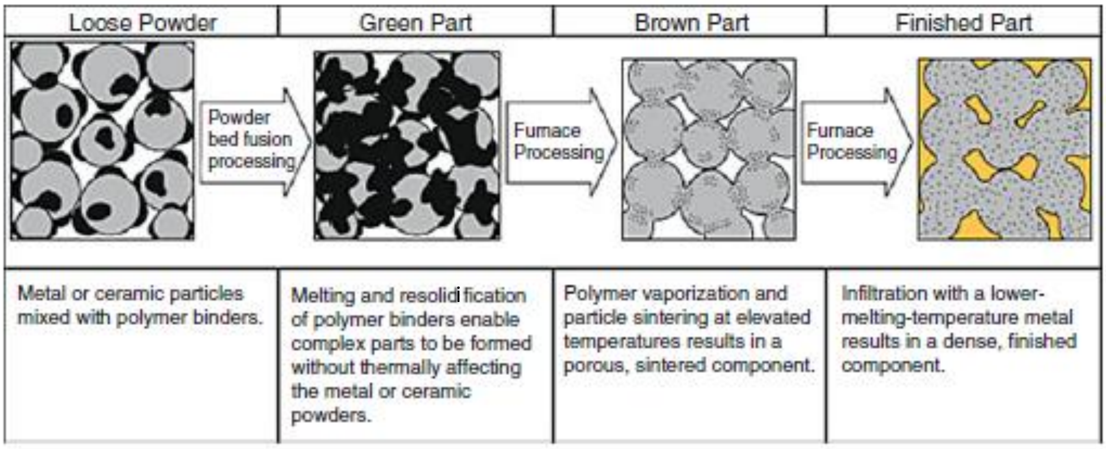


Figure 27 – Indirect sintering process for coated particles with polymer binders [3].

Powder recycling after sintering should be taken seriously, since the high temperatures inside the powder bed tend to sinter the remaining particles, creating agglomerations of increasing size (which need to be filtered). In any case, the tensile and compressive strength of the powder bed tends to increase with this additional sintering, which may minimize part deformation.

Additionally, the increased temperature of the sintered part may cause the surrounding loose powder to fuse to the surface of the part, creating a “skin”, with increasing thickness as the temperature rises. This part growth may be compensated in the part planning stage by offsetting the laser beam or part surface on the STL model.

Full melting is the most common mechanism for processing metal alloys, allowing increased bonding between the powder particles and higher density structures. The heat provided by the laser beam must be sufficient for completely melting the powder particles, from both the current layer and the previously solidified solid structure (creating a good bond between different layers). Superior laser power may be needed to provide the increased thermal energy required for full melting. However, the elevated temperatures may cause undesired part growth, which reduces process accuracy. This fact should be accounted for during part preparation and process parameters can be fine-tuned between sintering and full melting (for an intermediate result). Nevertheless, part density increases and porosity is reduced (although the resulting parts always present a certain degree of micro porosity, which must be considered for structural components). Thermal gradients may be increased with the higher temperatures, which can cause additional part distortion, proportional to the size of the part, an important fact to take into account when preparing the build job [3].

This theoretical review is especially interesting for understanding the underlying concepts and properties which have influence on the resulting mechanical properties of the produced components. A good comprehension of the raw material types and production mechanics was considered an important task to engage during this thesis. This knowledge will be increasingly relevant as soon as process validation and testing is started (experimental phases to be conducted in the future).

3.2. Laser Concepts

For laser-based additive manufacturing processes, laser know-how and experience is a major factor. With this in mind, some essential concepts were studied during the development of this project and their inclusion on this thesis was considered of great importance.

a) Laser Beam

A laser beam is a beam of light, with a given wavelength, which propagates mainly in one defined direction. In order to fully understand laser processing technology, some critical laser beam properties need to be defined and studied. Additionally, for choosing the correct laser components, these aspects need to be taken into account. With this in mind, some of the most relevant properties are explained next.

Laser Beam Shape

A laser beam doesn't propagate in a straight line from the process head to the part (figure 28). In fact, after exiting the optic path and passing through the collimator (described in the next section), it is focused on a certain point by the focal lenses. This way, it has a convergent shape until it reaches the **beam waist** (location along the propagation direction where the beam radius is minimum) and then adopts a divergent shape until interrupted (by the part, for example). Propagation is made along the laser axis.

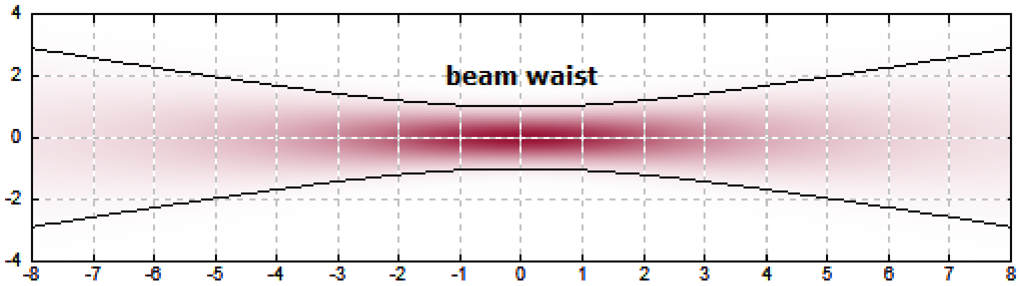


Figure 28 -Laser beam shape graphical representation showing the beam waist [37].

The beam waist may also be defined as beam focal point and its radius variation is critical for laser processing in AM. For example, for the LMD process, larger beam radius of up to 3 mm may be used with increasing laser power (compromising precision for additional deposition rate) and for powder bed systems, a smaller spot size of around 60 µm may be implemented to ensure maximum accuracy. Beam radius is usually defined by the variable w, measured in µm [37].

Beam Divergence (θ)

Following the beam shape concept described previously, a related property to consider is the beam divergence. This measures the speed of expansion of the laser beam as we increase the distance to the beam waist by the angle θ made between laser beam periphery and its axis of propagation. Beams with very small divergence are also called collimated beams. This property is usually measured in ° or mrad.

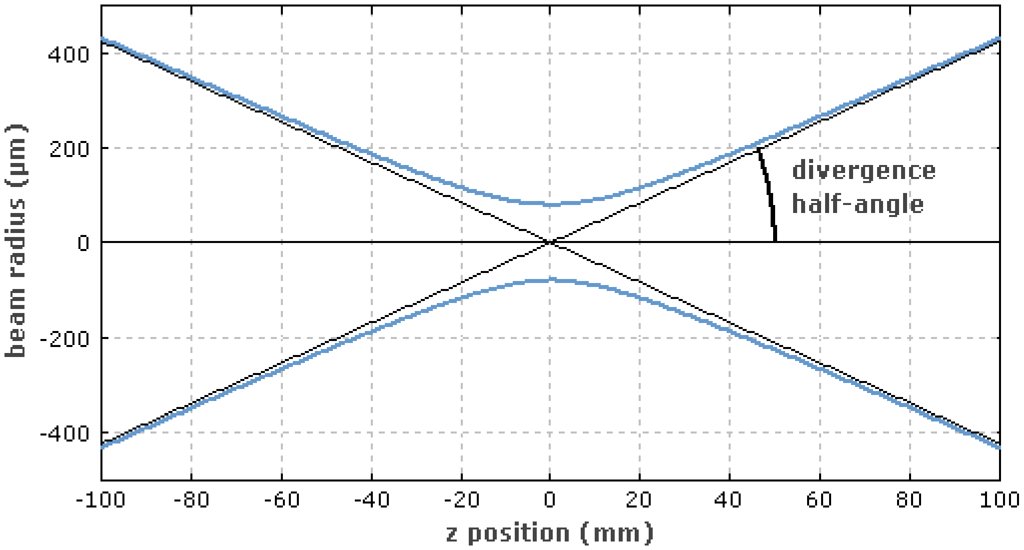


Figure 29 - Beam divergence geometrical representation [37].

Increased divergence is usually related to reduced beam quality, making it increasingly difficult to maintain a small focal point. This measure is also correlated with the M^2 quality factor and the Beam Parameter, as described next [37].

Gaussian Beam

A Gaussian beam is a theoretical laser beam with a very well defined profile, which propagates with a maximum intensity at its centre. This mode of propagation is usually used as a standard of comparison with the real propagated beam.

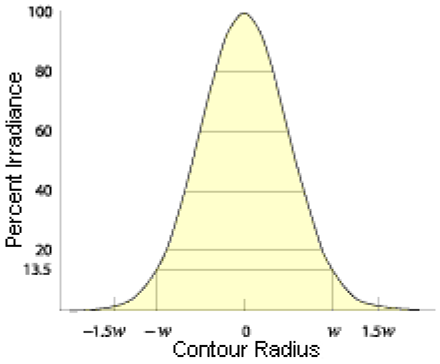


Figure 30 - Gaussian beam profile (theoretical laser beam mode). Maximum irradiance is achieved in the centre of the laser beam cross section [38].

Real laser beams propagate with different intensity profiles (different modes). Multimode laser sources produce laser beams with different modes combined, being usually associated with reduced beam quality and increased divergence (which may require larger fibre radius) [38].

M^2 Quality Factor

In order to quickly evaluate laser beam quality, the M^2 factor may be used. This variable may be correlated with beam divergence by the following calculation:

$$\theta = M^2 \cdot \frac{\lambda}{\pi \cdot w_0} \; (1)$$

where λ is the beam wavelength (which depends on the kind of laser source used, as described in the next section) and w_0 is the beam radius at its waist. For a Gaussian beam (with the perfect irradiance profile), the M^2 factor has a value of 1. For a real beam, this value is >1, with decreasing quality as the value increases [37, 38].

Beam Parameter Product (BPP)

Another beam quality indicator which is typically used is the Beam Parameter Product (BPP). As with the M^2 factor, which is linearly related, when the BPP increases, the beam quality decreases. For the Gaussian beam, the smallest possible BPP is given by λ/π. It may be calculated for the non-Gaussian beams by:

$$BPP = w_0 \cdot \theta \; (2)$$

Once again, w_0 is the beam radius in its waist (smallest radius value). The value is measured in mm·mrad. Different laser types achieve different BPP values, as can be seen in figure 31.

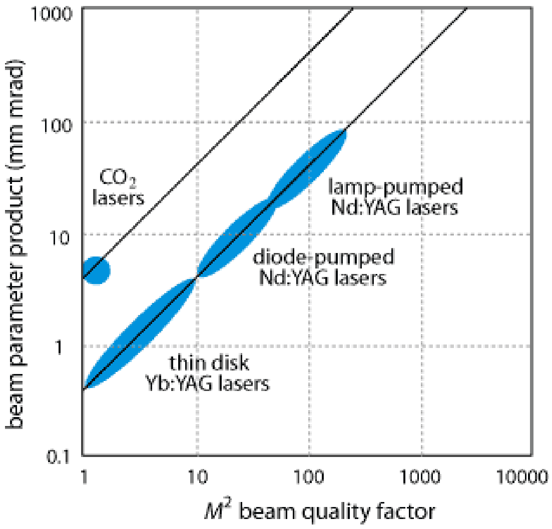


Figure 31 - Variation of beam quality in relation with the laser source type [37].

Other factors, such as non-ideal optics or imperfections in the optical system may increase the BPP and therefore, special care must be taken when managing these systems [37].

Rayleigh Length

The Rayleigh length is the distance from the beam waist (in the propagation direction) until the cross section where the beam radius is increased by a factor of $\sqrt{2}$ (and the cross section area by a factor of 2). Reduced beam quality (increase in the M^2 factor) is associated with a larger beam divergence and will decrease the Rayleigh length. For a Gaussian beam, the Rayleigh length, Z_R may be determined by:

$$Z_R = \frac{\pi \cdot w_0^2}{\lambda} \quad (3)$$

When the laser beam section has a large distance to the beam waist in comparison with the Rayleigh length, this region is usually defined as the far field. In opposition, the region near the beam waist is called the near field [37].

b) Essential components

In order to guarantee correct functionality of the laser system, all the essential components must be installed and considered throughout the machine project. The most critical modules that need to be integrated are explained in this topic. It should be noted that all optical components must be adapted to the wavelength of the produced laser beam, meaning that a system may not be compatible for different types of lasers.

Laser Source

The laser source is an obvious necessity for a laser system, since it is the responsible for supplying the laser beam for the process. Different types of laser sources are currently available, each with its functional characteristics. The following laser types are the most commonly used:

- **Solid-state lasers (figure 32):** this type of laser is produced by optically exciting ions contained within a solid host material. The host material (active medium) may have different geometries (rod, disk, fiber, slab) and is optically excited (by a lamp or a diode). For this, the solid host is doped (implantation of specific ions such as neodymium, Nd, or ytterbium, Yb, which are excited and emit the laser radiation). The emitted light has a wavelength around 1 µm, which gives the possibility to transport it by flexible glass fibres. Due to the nature of the emitted radiation, suitable eye protection must be implemented to protect the operator from potential eyesight damage;
- **Gas lasers (figure 32):** with a similar working principle, these lasers work without a solid host material. Instead, a gas (usually CO_2) is electrically excited (pumped) via two electrodes, creating the laser beam, which is directed out of the laser source. The gas may be mixed with nitrogen for increased pumping efficiency and helium for cooling. The gas mixture can be stationary or flowing. CO_2 lasers emit radiation at a wavelength of 10.6 µm, not allowing radiation transportation through glass fibre (instead, the optical path has to use mirror reflection).

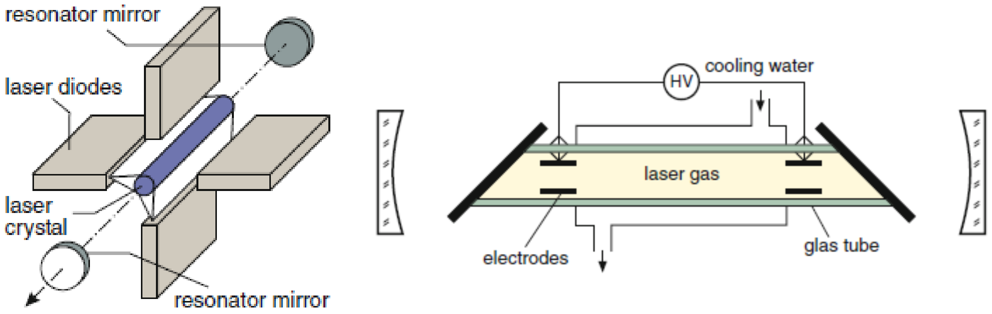


Figure 32 - Transversally pumped solid-state rod laser (left) and a schematic drawing of DC CO2 laser source (right) [39].

- **Diode lasers (figure 33):** also designated semiconductor lasers, the main difference from the previous laser sources is the lack of optical pumping, since the laser is directly pumped by supplying electrical current. By applying a voltage to the terminals of the diode, with its semiconductor material, such as gallium arsenide (GaAs) or indium phosphide (InP), radiation is emitted, not requiring the intermediate step of having to supply the electrical current to a lamp (pumping is made directly on the diode). Therefore, efficiency is increased (50 to 70%), in comparison with the previous laser sources. Since the diode component size is much smaller, although energy density is high, each diode provides only few watts of energy. Consequently, they are usually organized into diode bars, with increased output. Wavelengths for the emitted laser vary between 790 and 1080 nm [39].

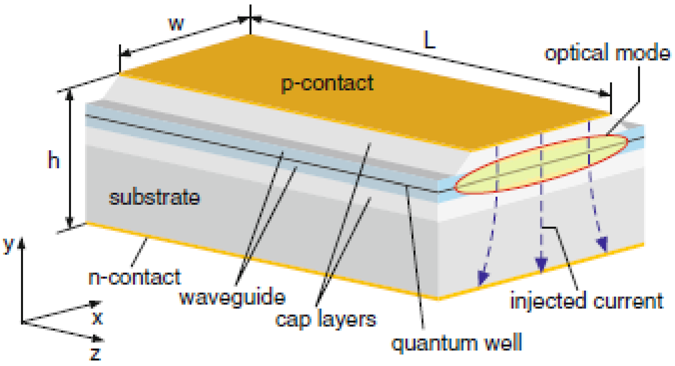


Figure 33 - Schematic picture of a laser diode. Typical dimensions: L = 1 mm, b = 200µm, h = 110µm [39].

Chiller

The chiller unit is responsible for cooling the laser system, as well as some of the other machine components. This equipment will be responsible for pumping the coolant to the laser source, as well as the collimator and other components (such as some deposition nozzles, for example). Deionized (DI) water is commonly used as a coolant, which requires compatible materials to be used on the circulation system (since it can be highly aggressive toward some of them, such as copper).

Flow rate should be considered when choosing an adequate chiller (being defined by the used pump) and the cooling power must be taken into account, depending on the desired temperatures (increasing power needs increasing cooling capability of the coolant when passing through the chiller) [40].

Laser head

The laser head is the machine module responsible for adjusting the laser beam for its specific operations. It contains the laser focusing unit, which is a set of dedicated lenses for adjusting the focal position of the laser beam (which must be regulated for different cutting operations, influencing the energy transmission to the working part or metallic sheet) and the focus diameter. This focusing operation is achieved within the attached collimator, described next.

At the end of the laser head, a process nozzle is attached. This component is chosen according to the required laser beam properties for a given process, influencing the achievable focal diameters and focus position.

A modular laser head conceptual schematic is present on annex A1, courtesy of HighYAG, including all the relevant modules which compose this system, such as the collimation unit and process nozzle (described further on).

Collimator

Attached to the laser head is the collimator, a required module which receives the diverging light from the optical path (such as the fibre cable) and produces a parallel beam, increasing its output quality. Additionally, it is responsible for the motor-driven focus positioning and diameter adjusting (working schematic from annex A1 contains information regarding the integration of this module into the laser beam path).

Laser Scanner

This component is specific for the SLM process, which uses a laser system for processing the powder bed region, in order to obtain the desired parts. Since the principles of this process require a horizontal 2-axis scanning of the powder bed surface, a laser scanner needs to be implemented. These components allow for a biaxial positioning of the laser beam on the working plane, deflecting it with high precision and speed (around 10 m/s positioning speed and trajectory spacing as low as 40 to 60 µm).

In order to accurately deflect the laser beam, the laser scanner uses two tiltable deflection mirrors, one for each planar axis, X and Y. These mirrors are attached to galvanometer scanners which control the rotation and the beam deflection angles, in order to position the focal point and scan the working plane, producing the intended shapes and trajectory vectors. A schematic view of this system is present on figure 34.

In order to adjust the focus position of the laser beam and provide vertical positioning (becoming a 3 dimensional adjustment), a dynamic focusing system may be coupled at the entrance of scanning unit, calibrating the beam focus according to the desired working plane and corresponding laser spot size. Alternatively, a scan lens may also be coupled to the beam exit of the scanner system for this end.

Besides laser-processing AM (like the SLM process), laser scanners may also be used for laser engraving, micromachining or welding.

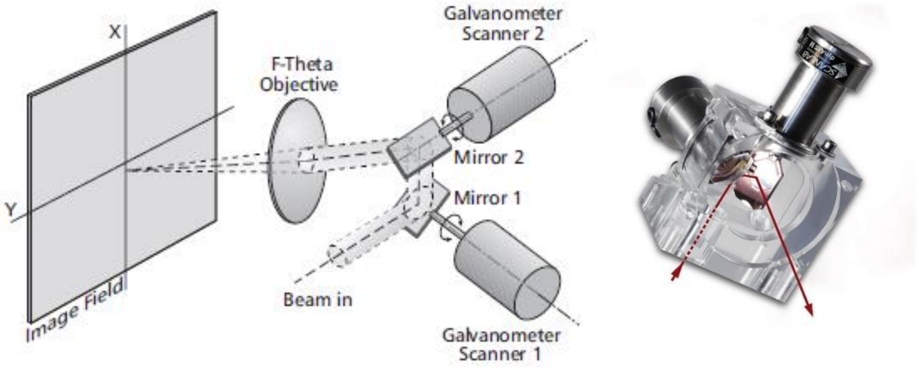


Figure 34 - Laser scanner working principle (courtesy of ScanLAB AG).

3.3. Machine Control

a) Main workflow concept

AM is a more direct approach to part production, largely based upon a computer aided (CAx) workflow, therefore good comprehension of the software necessities is critical to implement the involved processes. A possible workflow is described next:

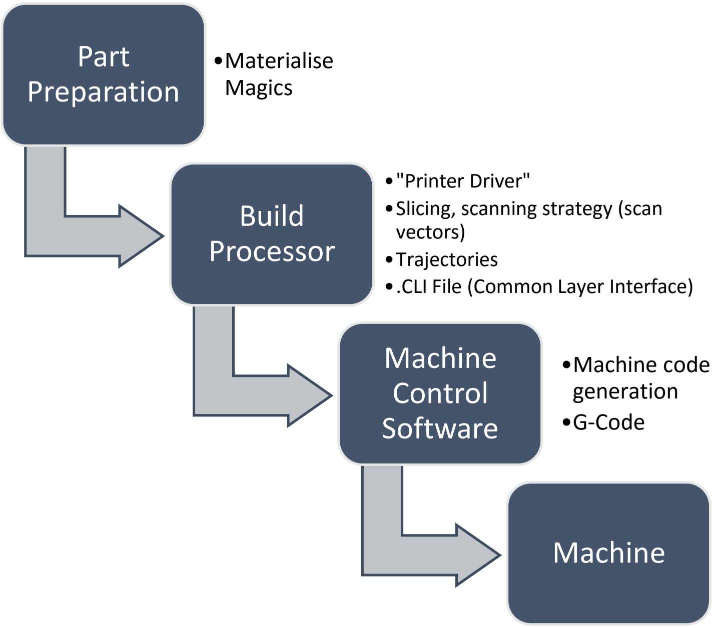


Figure 35 – Software CAx workflow schematic for AM operations.

As previously mentioned in this thesis, CAD part geometry is usually processed by using the STL file format, which configures exterior surfaces through triangular shapes. This file format is the most commonly used to describe the exterior surfaces, however new alternatives, such as the currently under development AMF (Additive Manufacturing File) format, are being considered, in order to overcome current STL limitations. This new format is planned to include new features, such as curved triangles (for increased accuracy with a reduced number of triangles in curved shapes), colour and surface texturing information, different material data and its distribution along the part. It is currently being developed under the ISO/ASTM 52915 – 13 standard [41].

Due to the complex nature of the metallic powder based processes, part preparation is critical for guaranteeing final part quality. This stage requires a dedicated software solution that analyses the final part geometry (usually obtained from a STL file) and detects critical shapes that can lead to defects. Topology optimization, support structure generation, wall thickness analysis or surface texturing are some of the current features that can be implemented on the 3D model of the part, resulting in a modified STL file, ready to be processed. Part offsetting that allows further surface post-processing may also be considered, making it possible to achieve the desired component finishing. The current industry standard is the Materialise Magics software, with a vast amount of possible add-on modules [42].

After preparation, the machine head trajectories (scanning vectors, for the SLM process) are programmed, based on the system characteristics. Part slicing is also performed, in order to define the different layers for production. This stage is carried out by a machine-specific build processor, resulting in a machine readable file. Next, the machine control software reads this information and transforms it into G-Code (machine code), which controls the different system modules, required for carrying out the process. Optimization of the post-processing strategies is an important factor to weigh in on the software side, since the working pattern may prevent distortion, high anisotropy and eventually speed up the process.

Different software may be implemented, slightly changing this workflow (for example, pre-processing and post-processing integration within the same package), although the main principles remain the same [3].

b) Metal AM features

Metal AM processes follow the standard workflow, although some additional care must be taken, since metallic materials are more difficult to process, usually involving increased thermal gradients. For example, specific support structures must be generated, not only for maintaining the part stable during the process (avoiding balancing structures), but serving as well as heat dissipation structures and holding the part in place on the build platform, preventing part distortion. Materialise Magics provides the SG+ module, which is specifically designed for the production of metallic support structures.

Since metallic powder is expensive and the process may be time consuming, Materialise also supplies nesting capabilities, which enable the user to optimize the building area usage with multiple parts within the same build job, taking into account their geometry. Additionally, other features like fixture design for confirming part fitting and easy modelling of specialized transportation packaging are also possible with the Fit2Ship module. Automatic generation of light-weight internal structures is also provided through a dedicated module, one of the main interests for AM, regarding design optimization [42].

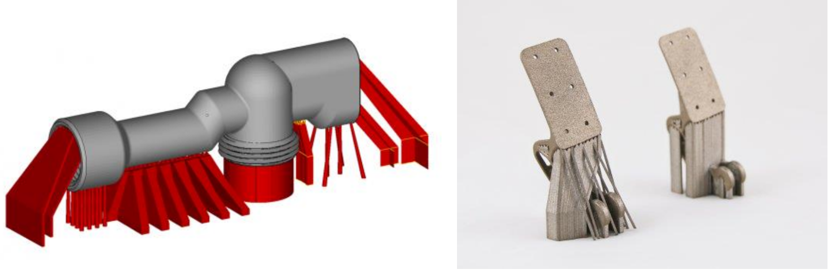


Figure 36 - Support generation using Materialise Magics SG+ module (left) and an example of produced metallic parts with the corresponding support structures (right) [42].

3.4. Laser Metal Deposition (LMD)

a) Principles of the process

The Laser Metal Deposition (LMD) process is contained inside the DED (Directed Energy Deposition) group and consists on the creation of metallic parts by powder fusion, through heating the material as it is deposited (figure 37). The energy is concentrated by using a laser or electron beam directed into the metal powder at the same time as it is supplied. Opposite to powder bed based processes, the material is not pre-laid inside the building chamber before heating. After heating, the molten metal powder will then be deposited onto an existing substrate (a flat plate for AM fabrication of the part) or part (for repair or geometry addition).

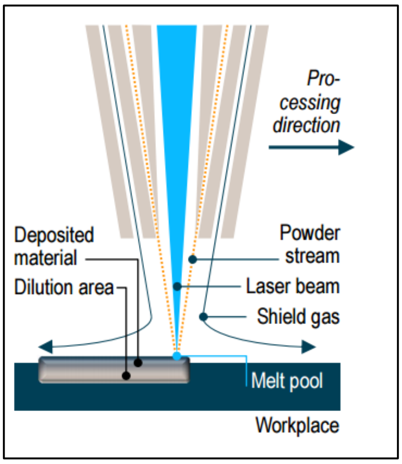


Figure 37 - LMD processing (with coaxial powder feeding). [12]

The material deposition in successive adjacent lines allows the creation of layers progressively producing the tri-dimensional part. For more complex shapes, it may be necessary the usage of support material, a multiaxial deposition head or substrate rotational movement. Existing systems can use from rotary tables to robotic arms, in order to achieve complex 5-axis movement capabilities. In these systems, nonvertical deposition is possible, allowing difficult build operations without support structures.

Within the processing area, a small melt pool is generated (ranging from 0.25 to 1 mm in diameter and 0.1 to 0.5 mm in depth). A small sized molten pool makes it possible to achieve high cooling rates and large thermal gradients, producing very unique microstructures of hardened material. Typical layer thicknesses range around 0.25 to 0.5 mm.

It should be noted that this process must not be mistaken for laser cladding or similar solutions, which are focused in surface finishing and repair operations by metal deposition. Correspondingly, this work will be focused on the process oriented for the production of the final part, starting with the 3D CAD data [3].

b) Typical materials

For the LMD process, it is intended that fully dense parts with mechanical functionality are obtained. Since the process is based on the development of a material melt pool, any powder mixture that can be held stable in this molten condition, can be theoretically used. Nevertheless, some important aspects must be considered: material reflectivity, thermal conductivity and oxidation sensitivity. Highly reflective materials can damage the optical system of the machine through laser reflection and will absorb less radiation from the laser source, thus making it more difficult to process. On the other hand, highly conductive metals tend to disperse heat more easily, not allowing enough temperature build-up. Oxidation sensitivity should be greatly considered, since it depends on the process conditions that can be maintained inside the system, with regards to oxygen content. Some manufacturers make use of full vacuum systems, instead of controlled inert atmospheres [3].

Powder size has a fairly large interval of available sizes to choose from. Anything from 20 to around 150 µm may be used and powder mixing is a possibility for producing alloy combinations during the deposition process (through multi powder feeding systems).

c) Known issues

There are some concerns related with the usage of LMD technology for the production of metallic parts. The major difficulties are related with the part distortion due to residual thermal stresses or anisotropy. To tackle these challenges, new deposition patterns are being investigated, such as producing shapes by separated punctual deposition and further joining. This way, thermal stresses are distributed and distortion is less probable.

Other alternative solution for this issue would be the usage of a different material for the internal section of the part with a low thermal expansion coefficient (such as nickel-iron Invar alloys). The external contour could then be deposited using the chosen material.

The need for support structures can also present some problems for the process. This substrate (composed by a copper alloy, for example) may melt when the metal is being deposited on top causing some rounding of part corners and other distortions. Some methods consisting on the deposition of a buffer layer between the substrate and the top layer are being considered, as well as the powder mixing technique which may reduce the issues of this interaction between support material and deposited metal. Nevertheless, support structures are not usually implemented, being replaced by multi-axial or hybrid processing (with posterior machining) [43].

d) Working head

The working head for the LMD process is often referred to as a “deposition head” and is the responsible module for depositing material onto the existing substrate. The process head usually includes the following functionalities:

- Laser optics for fine-tuning the laser beam focus point;
- Powder nozzle for supplying the necessary metallic powder to the process (further described in more detail);

- Inert gas connections for protecting the melt pool area;
- Sensoring system, usually by implementing a monitoring camera [3].

Additional information on the used processing head is available within the correspondent LMD machine project section.

e) Gas system

The gas system for the LMD system can be broken down into different necessary modules. For supplying the necessary shielding gas, a suitable Argon gas source (or other adequate inert gas) must be installed, with the correspondent connections to the laser process head or nozzle (depending on the adopted installation). For this project, the cutting assistance gas has to be considered as well, since a hybrid processing machine would be the final objective. The assistance gas is fed through the working head, maintaining the inside optics pressurized (further protecting them from possible powder that could infiltrate this very sensible system).

A correspondent exhaustion system must also be implemented, in order to maintain suitable atmospheric conditions inside the process chamber, avoiding a concentration of the resulting fumes from the powder melting operation. This system is usually implemented below the process table for the laser cutting process, since the fumes are directed downwards. However, for the LMD process, rising fumes are more common, hence exhaustion may be performed from the top. The exhaustion system must also be prepared for handling powder (in case of a possible infiltration) with adequate filtering equipment, capable of dealing with the powder grain size.

f) Powder feeding

For the majority of LMD systems, the powder supply is ensured in a similar way, by using a dedicated powder feeder, which regulates the amount of powder that is fed to the process area. The introduction of powder is made through the process head nozzle (further detailed afterwards) and its transportation is made by making use of pressurized gas (inert gas, such as nitrogen or argon).

In order to supply the metallic powder to the process nozzle, through the powder lines, it is necessary to include dedicated powder feeding equipment, which regulates and provides the transportation gas along with the build material (blown powder). There are off-the-shelf solutions available from different companies, such as Oerlikon-Metco (Switzerland), GTV (Germany) or FST (Netherlands), following a similar working principles. These solutions may be used for both AM operations as well as surface coating by atmospheric plasma spraying (APS) or High Velocity Oxygen Fuel (HVOF).

In these systems, the metallic powder is stored on dedicated powder hoppers, which can be heated, in case of high humidity conditions or water-sensitive materials, such as hygroscopic powders. This is made by using specialized heater jackets, ensuring that the powder remains free from moisture during spraying. Additionally, the material is continuously mixed by a stirrer, in order to ensure better flowing capability and correct mixture, in case of powder mixing. The powder is then supplied to a powder disk (figure 38), the component which regulates the feed rate, by changing its rotation speed and groove size (different user-replaceable powder disks are available).

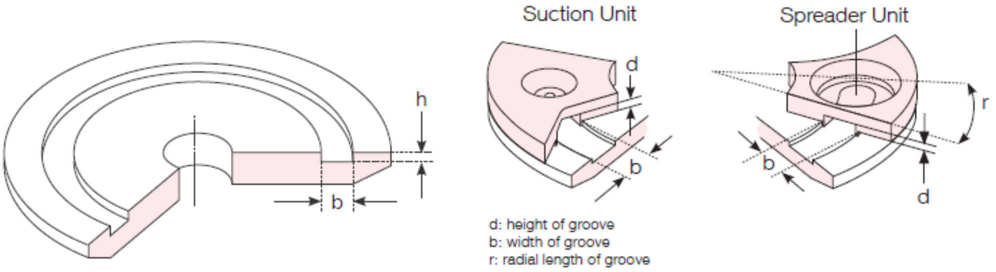


Figure 38 - Powder disk structure with its corresponding suction (entrance) and spreader (powder exit) units [44].

Entrance and exit of powder from the disk are regulated by the spreader and suction units, respectively, which also ensure that the disk is correctly filled. After completing a half turn, the powder is supplied to the corresponding process line along with the pressurized transportation gas (whose pressure is regulated by the feeder, as well) [44].

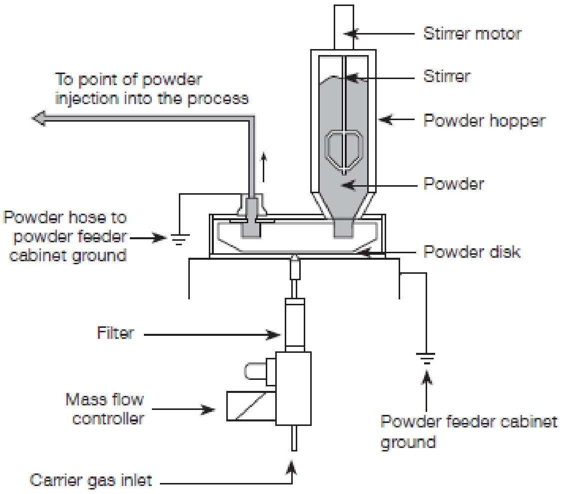


Figure 39 - Powder feeder functional principle, from the powder storage (hopper), passing through the powder disk and exiting through the pressurized powder line [44].

Different powder feeding methods can be adopted. One example is the system used by the Medicoat company, with their Flowmotion powder feeder (figure 40). The main principle is the same but the regulation of powder feed rate is made by an oscillating channel. The oscillating amplitude defines the quantity of powder that is delivered from the hopper. Although with a more complex working principle, this method presents some advantages regarding the lack of a stirrer to help powder transportation down to the channel and great particle size tolerance.

Figure 40 - The Medicoat Flowmotion powder feeder [45].

g) Process head nozzle

Different types of nozzles can be adopted for the LMD process. These can be coaxial, providing powder through the process head nozzle itself, or off-axis, which supply the material directly to the melt pool, outside the process head. Additionally, coaxial nozzles can provide both continuous and discontinuous coaxial powder injection (figure 41).

It should be noted that coaxial feeding provides better capture efficiency and better focus of the shielding gas, ensuring increased protection of the melt pool from oxidation (ideal for normal process atmosphere). On the other hand, it has the potential for being used on 3D cladding operations (entering the LMD process domain). Nozzle calibration is a critical step that should be considered, since powder efficiency could be greatly improved with the correct parameter set. Powder stream focusing point should match the laser beam focusing, in order to guarantee a good deposition operation [46].

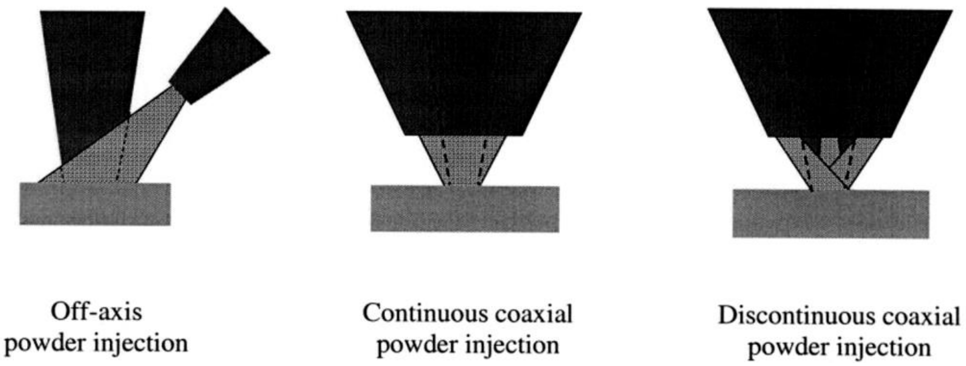


Figure 41 - Types of powder injection methods [46].

Off-axis powder nozzles

In the off-axis nozzle injection, the powder stream is positioned lateral to the laser beam. This should be as small as possible, in order to increase powder catch efficiency. Deposition will vary based on other factors, such as the nozzle inclination, distance to the part or opening type and size. Flow direction of the particles should be the same as the moving direction of the workpiece, in order to increase efficiency. On the other hand, for wider deposition tracks (5 to 25 mm), rectangular cross section of the nozzle opening can be a possibility to consider. The more conventional circular cross section should be used for tracks with 0.5 to 5 mm width (more precision work).

Single off-axis nozzles are simpler and therefore easier to implement, allowing lower equipment costs, although only usable for 2D operations. On the other hand, melt pool shape depends on the machine movement direction, which can affect properties uniformity. This can be solved by using a 4-nozzle configuration (each nozzle is equally spaced at 90 degrees around the laser beam), which creates a more consistent melt pool, although with less powder capture efficiency. Laser beam reflection is also a factor to consider, since nozzle exposure to this radiation can reduce its work life. Proximity to the melt pool can be an issue and therefore, water cooling is usually used to avoid long-term damage to the component.

Continuous coaxial powder nozzles

The first type of coaxial nozzles provides a powder stream that encloses the laser beam, therefore being called continuous. The working principle is based on splitting the powder stream from the powder feeder into three identical streams which enter the nozzle's expansion chamber. In this chamber, the powder is dispersed, leaving the nozzle in the shape of a hollow cone. Important process parameters include the apex angle of the cone, diameter of the powder stream focus, distance between focal point and nozzle tip and powder feeding properties.

Efficiency values up to 90% can be achieved (typical values range from 40 to 50%), depending on the ratio between the core diameter of the powder stream and the laser beam diameter on the workpiece. It should be noted that tilting of the process head with this nozzle is restricted, since it can disturb the homogeneity of the powder stream cone (a maximum tilt angle of about 20° may be achieved).

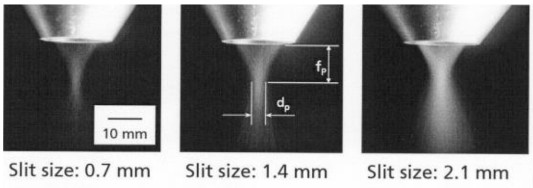


Figure 42 - Powder stream on a coaxial continuous nozzle and the influence of different slit (opening) sizes [46].

Discontinuous coaxial powder nozzles

This type of nozzles is characterized by having several individual powder streams distributed around the laser beam, forming a stream focus point on the laser beam. A common configuration consists on placing three powder exit holes equally spaced (“three-way nozzle” or “three-jet nozzle”). Once again, important nozzle parameters should be considered, such as the diameter of the powder stream focus, angle of the powder streams, diameter of nozzle holes, distance from the nozzle to the focus, powder feed rate and particle size. Powder efficiency may be varied by changing these parameters allowing for values up to 90%, although conventional values can range from 25 to 50%.

An important advantage of these nozzles is related to the capability of tilting the nozzle. Maximum tilt angles up to 90° may be feasible without critical issues, enhancing the build possibilities for the LMD process [46, 47].

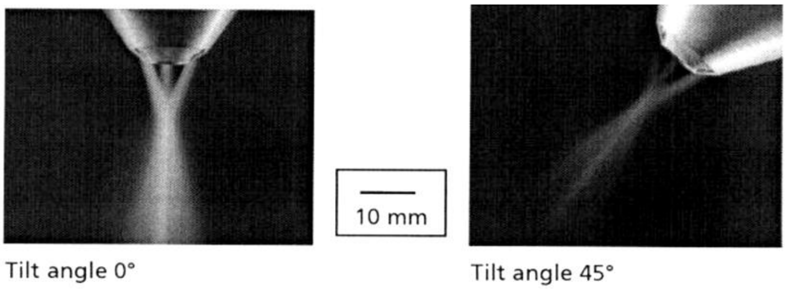


Figure 43 - Powder stream from a discontinuous nozzle with and without tilt angle [46].

Metallic material can also be introduced under the form of wire (not possible with a coaxial configuration and not a possibility with all metals). Wire feeding usually provides better capture efficiency and lower part porosity, although it is more indicated for simple geometries or surface coating. For more complex parts, where accuracy is critical, powder should be used [3].

h) Process monitoring

Process parameters are a very important factor to take into account for an AM process and these are material, application and geometry dependent. Incorrect parameter definition can cause final part distortion, processing failure or increased material waste. With that in mind, most manufacturers supply a set of parameters optimized for their machine, as well as for each material that is chosen by the user (from a limited selection). However, DED systems are usually more flexible, allowing the user to choose metallic powder from the vast selection made available by the suppliers, thus they should be carefully considered for the LMD process. Process monitoring and parameter studies have been carried out for laser cladding in the past, being increasingly important for the new AM applications, especially in high-responsibility component production, such as parts for the aeronautic industry.

Different parameters to consider include powder feed rate, beam power, traverse speed, track scan spacing and these can be regulated independently to achieve a smaller or bigger melt pool, as well as thicker or thinner deposits. Part strength is also influenced by the chosen parameters (for example, different scan patterns for each layer tend to decrease internal part stresses and give a more uniform behaviour) [3].

For the LMD process, the monitoring methods are centred on the same set of principles, mainly temperature measurement of the melt pool. Measurement of the molten material temperature is usually performed by analysing its emission intensity through the use of an infrared camera. Optical infrared imaging may be used to control the heat input and size of the melt pool, being the main method for regulating process parameters. A pyrometer may also be incorporated for measuring the temperature in the centre of the laser spot. An example of a possible setup of these components is shown on figure 44.

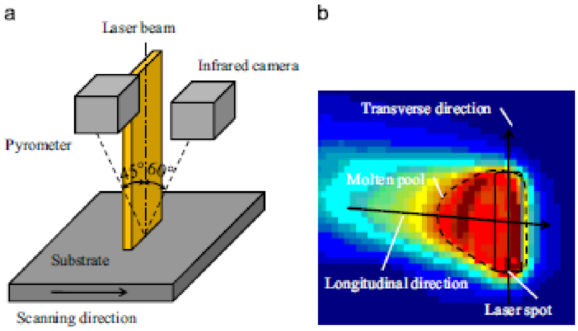


Figure 44 - An experimental setup of the optical components (a) for process monitoring and the usually used surface temperature measurement (b) [48].

In order to characterize the powder flow into the melt pool, a high velocity CCD camera may be used (figure 45), allowing for an estimation of particle velocity for control of the process feed rate. With an estimation of powder concentration, catchment efficiency may be predicted (allowing to evaluate the process performance, by calculating the ratio between the deposited material weight and the fed powder weight) [48].

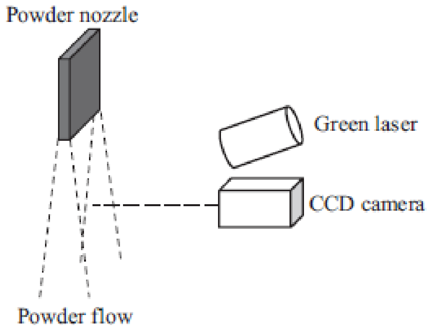


Figure 45 - Schematic of a possible CCD-based monitoring system with a green laser irradiating the powder flow for helping with the identification of the particles [48].

Although real-time offline data acquisition is a possibility with the existing solutions, interpretation is a different subject. In order to monitor the acquired data, analyse it and feedback it to the system for self-correction and process steering, further studying of this subject is necessary, being one of the current challenges that need to be overcome for AM processing.

i) Existing LMD systems

As part of every development process, a suitable analysis of the existing commercial system solutions related with the project objectives was performed. This way, information on existing LMD systems has been collected, with emphasis on Metal AM processing of large parts. This research benchmarking can be found on annex A2.

The interest of conducting these benchmarking exercises goes beyond the commercial advantages of knowing the existing competition. It serves as an evaluation of the current state of the art of existing market solutions, allowing to identify current reference characteristics and limitations, which will serve as a starting point for defining the final machine specifications and proposed objectives. Therefore, from an investigation and project development point of view, market benchmarking was considered a necessary task for this thesis.

3.5. Selective Laser Melting (SLM)

a) Principles of the process

The Selective Laser Melting (SLM) process is based on the powder bed fusion principle, following the ASTM standard F2792 – 12a, which consists in a selective fusion of metallic powder, by using thermal energy provided by a laser source. This process is similar to the SLS method, which is based on powder sintering. However, SLM causes the complete fusion of the powder metal, allowing greater particle bonding and the formation of high density structures. [3, 4].

The build process is based on the successive creation of fine layers of powder inside the system chamber, composing the so-called powder bed. A laser is directed at the surface of the powder bed, with its trajectories being defined by the scanner unit (previously described), which points the beam at the metallic powder, in order to transfer the necessary thermal energy for melting the material. The laser melts down several layers at once, in order to guarantee layer bonding along the vertical axis (layer-to-layer connection). After the part section contours and interior forms are made on the powder bed surface, a new layer is placed on top and the process is repeated successively. For constructing this powder bed, a common powder delivery system such as the one on figure 46 may be used:

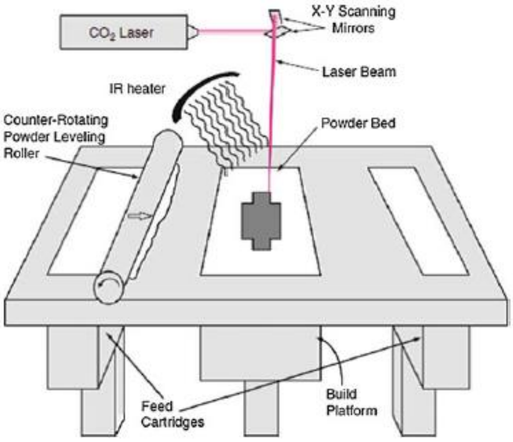


Figure 46 - Powder delivery system commonly used in SLM systems [3].

In this case, the powder is supplied on both sides of the building area (powder bed) by two feed cartridges (which move the powder up into the chamber). A roller is responsible for levelling the powder layer over the powder bed for processing. The powder bed itself is moving downwards (according to the desired layer thickness), allowing for the successive layers to be made on top of the previously processed ones. An alternative configuration is the use of a hopper-based delivery system (figure 47), in which the powder is delivered from above, rather than beneath. The material is deposited in front of a dedicated leveller and ultrasonic vibration may be used for helping to fluidize the powder.

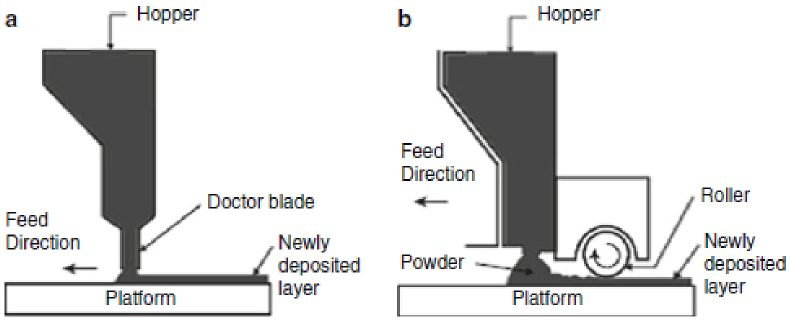


Figure 47 – Hopper-based delivery systems: hopper feeding system with a levelling blade (a) or with incorporated roller system [3].

The different metallic alloys that are used can vary from more conventional materials, such as aluminium or steel, to more specific high demand materials, such as titanium, cobalt-chrome or nickel alloys. Powder metal for the SLM process is similar to the one used for LMD operations (described previously). Nevertheless, since this process is usually related to high precision part production, finer grain is usually employed. Typically, the part can be used after removal from the machine, possessing adequate physical properties for mechanical work.

The process parameters are of great relevance for the production of resistant parts and therefore, there are a group of variables that need to be taken into account:

- **Laser parameters:** power, focal point size, pulse duration, frequency;
- **Scan parameters:** scan speed, spacing, scanning pattern;
- **Temperature parameters:** powder bed and feeder temperature, temperature gradient inside the system [3].

It is usual to create an inert atmosphere inside the system, preventing oxidation of the metallic powder and potential loss of mechanical properties (environmentally controlled chamber). Produced parts may contain thousands of layers, with a typical thickness between 20 and 150 microns, taking hundreds of hours to fabricate, therefore good processing conditions must be assured, in order to guarantee the success of the build job. Some metals require a heated powder bed, in order to reduce temperature gradients, which may cause part distortion [22].

After production, the part will be located inside the powder bed and should be removed, cleaned and, if necessary, post-processed. The immersion of the part inside the powder could be seen as an advantage, since it may not require the production of support structures as situations with lack of part balance are not common. However, support structures also serve the purpose of dissipating heat from the part, guaranteeing that excessive temperatures gradients occur, which may compromise the final result, therefore being of great importance.

As seen on figure 48, several specific components are used on SLM systems, such as the laser scanner (previously discussed in the correspondent section) or the powder storage, delivery and layer distribution systems (mentioned previously and described in more detail on the SLM system development section).

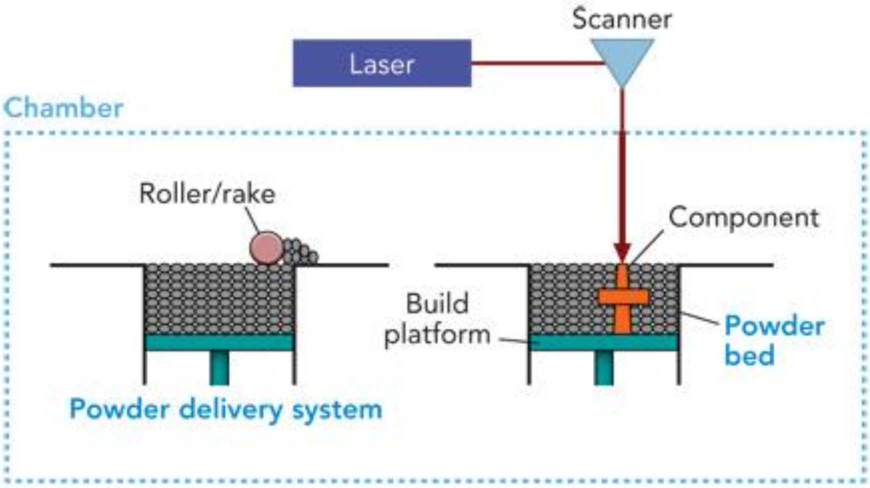


Figure 48 -Schematic representation of a AM PBF system [22].

b) Typical materials

Although the used metallic materials for SLM systems may be similar to the ones used for LMD processing, these present different characteristics, especially when it comes to particle size. Blown powder systems (such as LMD equipment), can operate with particle sizes above 100 microns but this doesn't necessarily translate to powder bed machines.

PBF systems operate best with particles in the range of 30 to 45 microns (smaller particles are also possible and some manufacturers such as Concept Laser provide layers with as low as 20 micron thickness, although flowability issues must be accounted [49]). These systems allow, therefore, for great precision and detail for the produced structures. Additionally, it is important that the particle size range is as narrow as possible, therefore providing a dense plane on every layer deposition. Particle size must account for the desired layer thickness and should be sufficiently smaller, in order to provide higher layer compaction [6].

The majority of SLM systems manufacturers are also suppliers of their own powder material. Since optimizing process parameters is a very challenging task, this measure allows more control from the system developers over the processing results of their machines, as the possible machine/powder combinations are fewer. Moreover, this is also an important source of income, hence most machine developer support is only provided when these powders are used.

c) Powder management concerns

Several powder delivery systems have been developed for PBF processes, so a standard solution doesn't exist. Nevertheless, although any manufacturer can freely design these systems, they should meet several characteristics, in order to ensure correct working conditions for the AM process:

1. The powder storage unit should be able to supply the necessary powder quantity to fulfil the work chamber, if possible enabling the process to achieve maximum build height without the necessity to pause the machine for a refill.
2. The powder handling system must be able to deliver the correct powder volume to the build platform, in order to sufficiently cover the previous layer, avoiding waste or excess deposition on a new layer formation.
3. The powder spreading must be smooth, respecting the desired layer thickness, in a repeatable fashion.
4. Powder must be spread without creating excessive shear force that could disturb the previously processed layers.

Powder feeding itself presents complex physical challenges that should also be considered, along with the powder handling conditions previously described. Correspondingly, particle size plays an important role in the feeding process: as particle size decreases, flow capability is diminished, due to the increase of inter-particle friction and electrostatic forces. This way, for systems that support different grain sizes, it must be assured that particle flow has been considered for all compatible size distributions.

Special metallic materials are used for additive manufacturing and usually present an important advantage for this type of processes, due to their low density and specific mechanical properties. However, these can also be highly reactive and prone to oxidation or even explosive behaviour. To prevent any accidents or loss of part quality, it is usual to provide an inert atmosphere for the powder and throughout the process (which will increase the system complexity, since new atmosphere control modules must be developed).

The use of powder material can also present issues related to its tendency to become airborne and float as a cloud of particles. This situation should be avoided while feeding the system, since it can cause damage to the internal machine components by accumulation of particles or even powder burning. Additionally, the system must be sealed, to ensure that the operator is safe from these potentially hazardous materials (especially when inhaled). Otherwise, adequate protective gear must be used (such as gas masks, lab coats and gloves), to safely handle the machine.

The previously mentioned problems are exacerbated with the use of finer powder. However, smaller grain size usually provides better surface finish, higher accuracy and thinner layers, therefore improving part quality. In conclusion, a balance must be established and the smallest powder size should be used, while assuring that no issues will arise from its use [3].

d) Powder Recycling

As current SLM systems tend to become faster and increasingly large, powder management concerns tend to be given additional importance. Since the process itself requires that more powder than needed for building the part is supplied, excess material occurs in every build job. Furthermore, metallic powder is an expensive resource, making material recycling even more relevant for these new systems.

However, unused powder may not be used directly, since it can be chemically changed by the temperatures and process gases inside the building chamber. Additionally, material surrounding the built part tend to fuse due to the influence of the laser beam on the surroundings of the process area and splatter may occur after forming the melt pool. Fused powder will originate different shapes and grain sizes, which cannot be mixed with the original powder, at the expense of affecting the next parts planned for production.

Therefore, unused material from the powder bed should be filtered (usually using a sieving unit). On the other hand, excess material from layer deposition (overflow powder, which serves as a guarantee for good formation of the powder layer) may also be reused. One technique for recycling all these materials is based on creating a mixture with 1/3 filtered build platform powder, 1/3 excess powder and 1/3 unused powder. Good mixture is critical for the success of the following build jobs [3].

Some automatic powder processing units have been developed, in order to optimize the SLM process with sustainability in mind, such as the PSX Sieving Station, which integrates the SLM

Solutions 500HL system. This fully automatic powder sieving system filters the excess metal powder from the build process and delivers a container with ready-to-use recycled powder [50].

e) Process monitoring

Due to the nature of the layer-by-layer build-up operation and rapid solidification, the SLM process relies on complex thermal gradients and heat transfer mechanisms. Therefore, special microstructures are created and potential defects like micro-porosities, lack of fusion between layers or general part distortion are common, especially for large parts, hence the challenge for qualification and certification of this process.

In order to monitor the SLM process in real-time, making it possible to guarantee final part quality and avoid scrap after long hours of part building, process monitoring methods have been implemented, like previously mentioned for the LMD process. It is necessary to guarantee quality, consistency and reproducibility across the different processes and systems.

First of all, machine state monitoring should be implemented, in order to maintain correct machine conditions. For example, monitoring solutions QMatmosphere by Concept Laser and EOSTATE Base by EOS regulate the oxygen concentration inside the process chamber, throughout the build job, in order to avoid part oxidation. Other parameters, such as laser power and focus or scanner calibration are also regulated, in order to maintain ideal melt pool sizes and temperatures. Melt Pool Monitoring (MPM) by SLM Solutions is due to be released in 2016 and follows the same principles described previously on the LMD section (detection of thermal radiation and build parameter optimization). The similar QMmeltpool system has been developed by Concept Laser, using a high-speed coaxial camera with the objective of extracting thermal information from the melt pool and further control the laser parameters (figure 49).

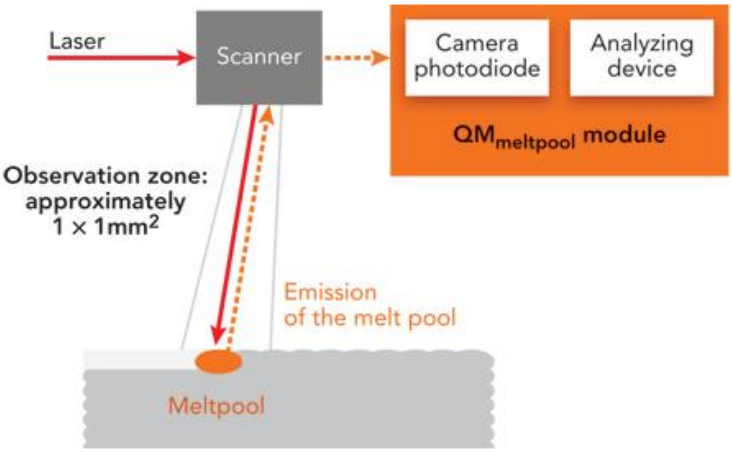


Figure 49 - Concept Laser's QMmeltpool system for analysis of light emissions from the melt pool, providing temperature readings during the process [22].

Other monitoring solutions, specific for the SLM process, have been developed, like the powder bed layer deposition control. For example, SLM Solutions' Layer Control System (figure 50) photographs the powder bed surface after each re-coat and after laser processing and then automatically analyses the captured images, in order to detect anomalies on the produced parts and stop the process for the defective ones (in case multiple copies of the same component are being built). QMcoating by Concept Laser monitors the powder dispersion throughout the built layers, allowing for compensation of the layer thickness and guaranteeing a uniform layer deposition [6, 22].

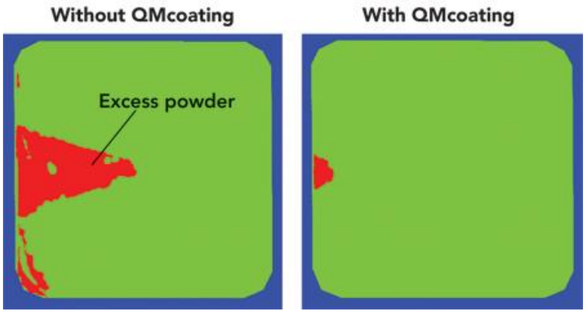


Figure 50 - Concept Laser's QMcoating system for monitoring powder dispersion and layer thickness after recoating [22].

f) Existing SLM systems

Following the analysis previously carried out for the commercially available LMD systems, the current SLM process applications have also been researched. Although less variability is found on the current SLM market, in comparison with DED processes (which have a much longer background from laser cladding), some important solutions that could serve as a suitable benchmark were found. This benchmarking is collected on annex A3.

Once again, this benchmarking exercise was a vital task for getting a perspective on the existing market solutions and potential opportunities for a new differentiating approach. This way, the specifications of the final system may be defined, with a good knowledge of what is currently available on this sector.

3.6. Theoretical Review Conclusion

As with any new process implementation, a good knowledge of the involved concepts is necessary to guarantee informed and accurate decisions. During this thesis, both a generalized approach on the Additive Manufacturing domain and a more specific and extensive analysis of Metal AM processes, namely LMD and SLM, was made. Other common concepts, such as metallic powder materials and production methods, laser technology concepts or machine control workflow were also considered of great interest for this endeavour. All the research topics were chosen based on the necessities that were verified throughout the different stages of this project, which created the need for this specific investigation.

The selected concepts for this theoretical review were considered important for both the short-term implementation, as well as for the future experimental validation and testing. Therefore, not only they were relevant from an academic point of view, but they can also be practically applied and useful for the final machine project. The knowledge of the process advantages and limitations is vital for assuring that a good workflow and approach to these topics is accomplished.

4. ADIRA Metal AM Plan

4.1. Company Background

ADIRA’s company background as an industrial machinery manufacturer is well known in Portugal, as it is the main industry player for this specific market segment, with the largest market share. Founded in 1956 by António Dias Ramos (hence the name ADIRA), it has 60 years of experience in machine tools building. The company’s focus is not only on Portugal, but also on the worldwide market, currently exporting to more than 40 countries. External market is currently the main source of income for ADIRA.

ADIRA’s systems portfolio is oriented for sheet metal manufacturing, including press brakes, mechanical shears and more recently the development of laser cutting machines. Experience in this last type of systems accounts for more than 15 years. More recent products include custom automated production lines, with robotic cells and automatic storage systems. There is a competitive advantage for special “taylor made” solutions and custom developments, which are considered of great importance for the company [51].

There has been a permanent investment in scientific research and technological development, in order to keep up with the most recent market trends. Important cooperation relationships are established between ADIRA and other industrial and research partners (as patent throughout this project). Therefore, the entrance into the Additive Manufacturing segment was a logical step for the company, since this area is becoming increasingly influent in today’s production technology.

This new endeavour distances itself from the traditional sheet metal machinery and requires the contribution of the acquired knowledge in laser technology, being this area the main driver for Metal AM operations. Close cooperation has been established with a laser technology institute for the initial process engineering, which will be further explained in this report.

As the laser-cutting systems are of great importance for this project, serving as the base platform for the described developments, more detailed information on the current ADIRA Laser-Cutting range is present on annex A4.

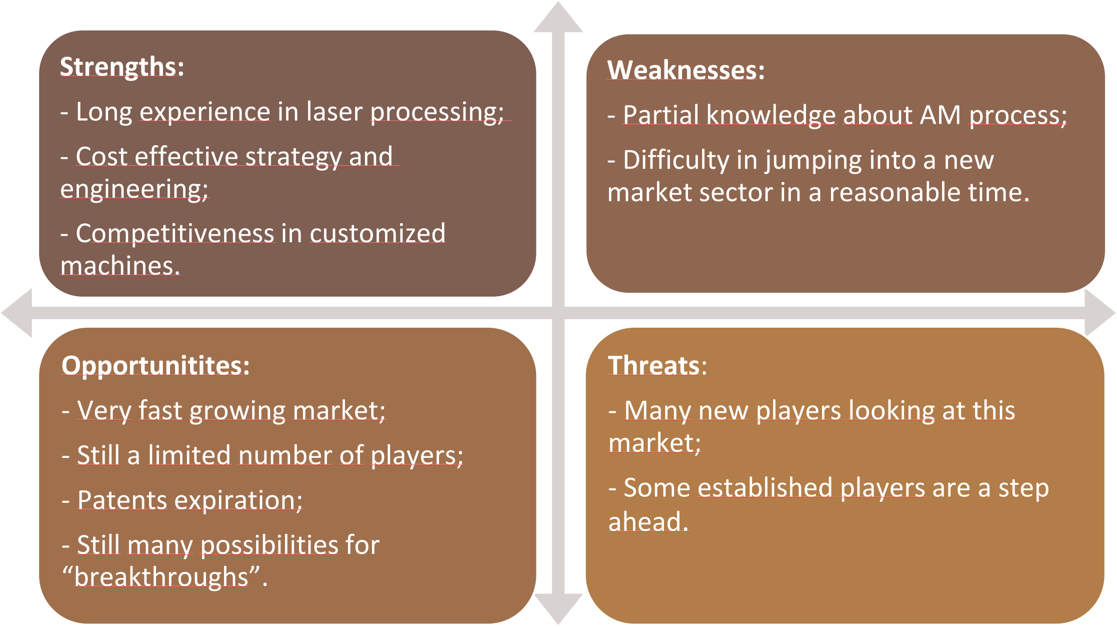
4.2. ADIRA’s Project Objectives

In order to have an important competitive advantage and successfully enter this new market segment, ADIRA has decided that system production should be undertaken on the two existing types of laser additive manufacturing machines: powder bed and powder-fed. For the first type, a SLM system was planned for development and for the second, a LMD machine project was defined. These technologies have been previously described and project details are further presented on this report.

a) Current situation

ADIRA’s plan is focused on exploring the existing possibilities in these new market and industrial trends. Therefore, the machine development projects for large AM metallic parts are centred on a specific market niche, which is becoming more relevant each day. The final objective would be the production of systems which could also provide large production rate, with a focus on production line integration (making AM part of the existing productive chain).

Since existing company know-how is centred on sheet metal processing, a lack of knowledge of AM processes is an obstacle that needs to be considered. A simple SWOT analysis of this situation (figure 51) can help to further clarify this situation:



Strengths:

- Long experience in laser processing;
- Cost effective strategy and engineering;
- Competitiveness in customized machines.

Weaknesses:

- Partial knowledge about AM process;
- Difficulty in jumping into a new market sector in a reasonable time.

Opportunitites:

- Very fast growing market;
- Still a limited number of players;
- Patents expiration;
- Still many possibilities for “breakthroughs”.

Threats:

- Many new players looking at this market;
- Some established players are a step ahead.

Figure 51 - SWOT analysis for ADIRA's Metal AM project.

Therefore, a cooperation policy was established for gathering important partners for the different areas of interest (such as powder metal supply and specific equipment, dedicated software solutions and process research). Both industrial, academic and research partnerships were considered for this joint development. Nevertheless, it should be noted that laser knowledge is very relevant for the proposed project and an existing advantage (considering ADIRA's laser-cutting machine range), since it is a central part of these technologies.

b) Established partnerships

For establishing the necessary partnerships for the development of the AM project, different areas of interest were considered:

- **Process development:** for developing the necessary processing capabilities, important R&D work was carried out in cooperation with a laser technology institute, which collaborated on the concept development;
- **Powder supply:** the required materials for developing metallic parts (metal powder) and the corresponding feeding components were developed and guaranteed by a proven market supplier;
- **Software:** the necessary pre and post-processing software for the SLM part build-up was supplied by an experienced developer; for the LMD project, the same laser technology institute supplied the software;
- **Machine control:** for controlling the system, ADIRA used an existing connection with its usual supplier for machine control and movement components of the current laser-cutting systems.

c) Objectives Summary

As previously stated, this new entrance into the AM segment is viewed as a joint venture of ADIRA and several partners, whose cooperation provides bilateral advantages, both for R&D knowledge development and in a commercial perspective. In order to make this entry into the AM market successfully, several objectives were defined, along with the steps to be taken after starting the development:

- ✓ The LMD system project, being a shorter term development with the planned development of a dedicated system. Additionally, a possible feature pack for the existing laser-cutting systems could be created, in order to add LMD process capabilities to the original machine;

- ✓ The SLM system project, with a more long-term development, due to the increasing complexity of the process implementation (as described later in this report);
- ✓ A parallel system (AM simulator) would be developed, which would be dedicated for public unveiling of the AM range by ADIRA. This demonstration system would include both LMD and SLM processes and would serve for initial validation, as well as process development for both technologies. This system development will be included within the time frame of this thesis.

The details of these different projects that compose the ADIRA Metal AM plan will be described in the next chapters, along with the developments made within the scope of this thesis. A schematic of the described plan can be seen next:

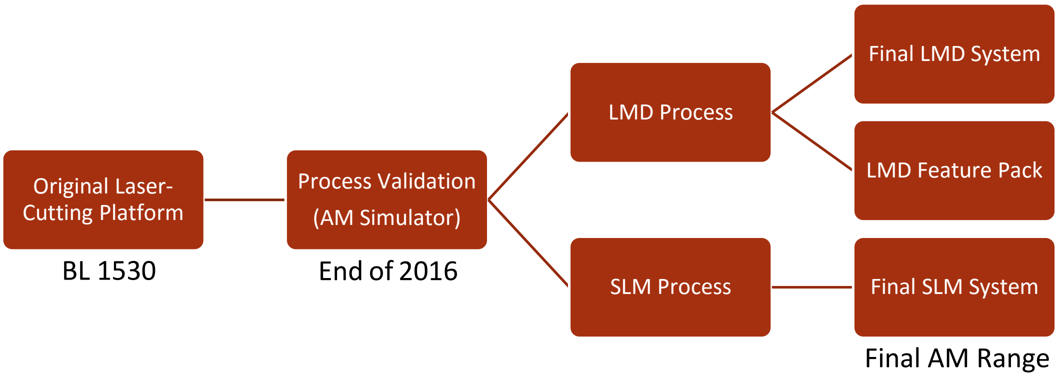


Figure 52 - Scheme for the AM development project.

5. LMD System Project

This chapter will be focused on the description of the proposed LMD project and its development. The objectives will be explained, as well as the approach adopted (figure 53), which included an important collaboration with other industry technology partners, since this was a new market segment for ADIRA. This external support was a complement to the internal teams' knowledge, along with the contribution of FEUP, specially the Mechanical Engineering department.

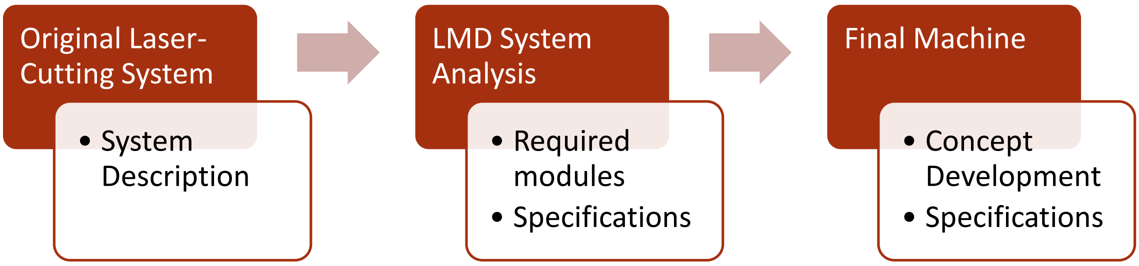


Figure 53 - Workflow for the LMD system project analysis.

5.1. Original Laser-Cutting System

The more short-term project was based on the DED technology, more specifically LMD. For this endeavour, ADIRA decided to make good use of the existing know-how on laser cutting technology, a solid platform for this new process.

The proposed laser-cutting system for serving as a start point for this project was the ADIRA BL 1530 system (figure 54). This is the smallest laser-cutting platform currently under production, although providing a work area of 1500 x 3000 mm (a very interesting working envelope for AM operations). With a positioning speed of 80 m/min, 0.05 mm positional accuracy and high movement acceleration (over 1G), it was considered a suitable platform for implementing in the LMD and SLM processes [52]. More information on this system and other machines from the ADIRA laser range is available on annex A4.

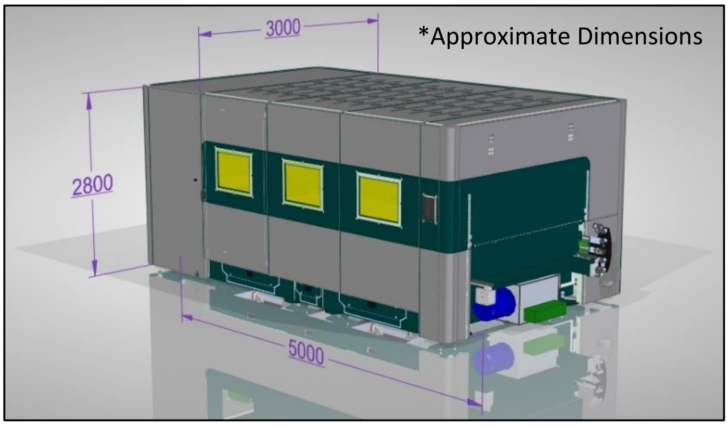


Figure 54 - CAD model of the original BL 1530 laser-cutting system.

The defined work plan included several phases, starting with a necessary process validation for concept testing, prior to developing the LMD system. Afterwards, two different paths were proposed. The first one consisted in creating the necessary capability on the original BL 1530 platform for easy retrofitting and installation of the AM capabilities, while maintaining all the remaining components (a new optional feature pack for the BL system). This way, the original laser-cutting machine could also be used for laser cladding and surface processing, allowing for light AM operations. The second approach would be more focused on the additive manufacturing operations; however, it was determined that the original platform work volume wasn’t competitive for such work.

The main issue was related with the vertical movement capability, which was appropriate for sheet metal processing but not for 3D part production. The majority of AM systems present a more balanced relationship between vertical and horizontal dimensions. Additionally, a 3-axis approach is also less suitable from a versatility point of view, hence this fact would have to be reconsidered in the future, possibly with the implementation of a multiaxial system.

With this in mind, the platform would have to be adapted, increasing vertical dimensions, which would lead to important structural changes. Nevertheless, the approach to be adopted for the development of the final ADIRA AM machine range would only be decided after evaluating market reception to the first prototype of this concept.

5.2. LMD Specific Modules

As a first step in the proposed work plan, the process validation and preliminary testing was conducted. In order to maximize the use of an existing laser cutting system, it was decided that the project should address the necessities involved in adapting the platform for AM operations, simultaneously including most of the already developed machine components and structural modules. Following this strategy, most of the structural, movement and command components from the original system were kept. However, since new capabilities, such as powder deposition must be included, the necessary additional modules had to be chosen and incorporated in the laser-cutting platform.

The core component for the development of this system was the process head nozzle. This part was developed and projected with the intent of replacing the original cutting nozzle, while being able to be retrofitted, being fully compatible with the system. The new nozzle would have the necessary input connections and adaptations for metal powder supply which combined with the laser power, would allow the deposition of molten material. Accordingly, all external components for powder feeding would need to be included.

a) Processing Head

In order to increase system versatility, it was considered the possibility of combining metal deposition processing with laser-cutting, by simply exchanging the correspondent nozzles. With this in mind, a suitable process head must be installed, in order to be able to adjust the focusing length for both processes and maintain ideal process conditions.

Accordingly, a prototype process head was developed, with an extended motorized Z-axis travel (additional focus positioning capability) and a focal length of 200 mm. This processing head has a compatible collimation module already attached and can fit both a standard laser-cutting nozzle and the compatible LMD nozzle, with additional powder feeding inputs (as described next). The lenses are compatible with diode laser beam wavelength, as necessary by the chosen laser source (a 4 kW diode laser).

b) Process Head Nozzle

The development of a LMD nozzle that could be used with the existing laser system was planned for the implementation of this process. This nozzle should be compatible with the existing laser head, in order to minimize the required adaptations during installation. The resulting product was a coaxial continuous nozzle, water-cooled with three powder injection input connections. The coaxial nozzle allows high deposition accuracy and a more precise powder feeding, although not being recommended for tilting process heads (it is able to withstand head inclination until approximately 20°). The three-jet design enables the focusing of the powder flow, important to achieve high melting and deposition rates. For implementing rotation on the process head, a new type of nozzle should be designed (such as previously discussed, a discontinuous coaxial nozzle).

Additionally, for the water cooling of the nozzle, two corresponding inputs were provided. Since this nozzle has a copper-based body, special care would have to be in place regarding the liquid coolant. The current water-cooling system for the laser-cutting machine uses DI water (deionized water) for refrigeration of the laser source and collimator. However, as the nozzle body is copper-based, an alternative would have to be defined [53].

This coaxial nozzle uses a three-jet design (with three powder inputs). Therefore, the powder flow would need to be split into three different lines. This was achieved with a dedicated powder splitter, which should be placed close to the process nozzle (figure 55) [54]. A 3D CAD model was produced from the correspondent 2D drawing for integration on the machine simulator CAD project (described later on).

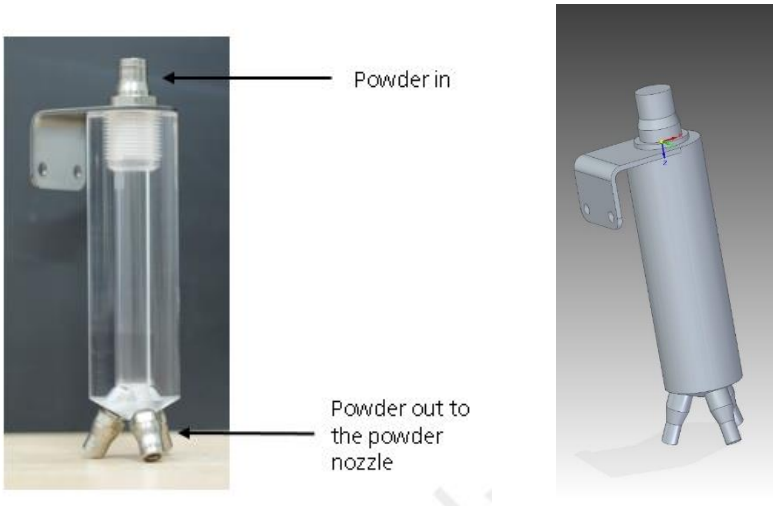


Figure 55 – Powder Splitter component (left) and the produced CAD model from the supplied technical information (right) [54].

c) Laser Source

For the LMD process, high energy is relevant for high-speed applications. On the other hand, spot size may not be as small as for the SLM, for example, since the main interest is the heat transferring capacity, that should be enough to efficiently melt the powder metal that exits the nozzle. Nevertheless, the focus point of the laser should match the focusing point of the powder stream.

A diode laser source was chosen for this application, combining high efficiency with the interest of testing this rather new technology for both laser-cutting and metal deposition. Additionally, a high power source was also selected, in order to provide higher versatility and eventually allow testing of higher deposition rates.

d) Powder Feeder

In order to supply the metallic powder to the system, a dedicated powder feeder had to be selected. For this purpose, a standalone powder system was chosen (figure 56), since it allows individual operation, which is an important feature for the development of a new process (allowing for easier configuration and troubleshooting). Nevertheless, control of the Powder Feeder through the machine control is possible and is planned for the final system. In addition, a great range of powder feed rates are possible with this system and the different provided features are adequate for this project.

Figure 56 - The standalone powder feeder [44].

This equipment was configured with two separate powder hoppers, each with 1.1 l capacity. The parallel hoppers make it possible to fill them with two different powder types, allowing build-up with special mixed alloys or fabrication of Functionally Graded Materials, by alternating material types. Additionally, they can also be used with the same type, in order to increase the total capacity for feeding.

Although the system has the capability for varying the powder feed rate, the range of achievable values depends on the powder disc sets that are assembled, more specifically their groove size. For process testing and validation, a large range of feeding rates is always interesting, hence different discs were considered besides the included standard one, both allowing lower feed rates for precision deposition. For communication with the machine control, a Profibus interface was included.

e) Software

As a necessary complement to the chosen hardware, an adequate software solution must be used, giving the possibility to successfully produce the desired parts and LMD operations. Several options are currently available, such as Autodesk's Netfabb, a software solution that ranges from private to professional applications and allows STL optimization for 3D Printing (pre-processing). Other possibility is the more well-known solution from Materialise, the Magics software suite (described further in the SLM section).

Nevertheless, since the mentioned solutions are not well-proven for LMD processing, it was decided that a different approach would be followed. Therefore, a dedicated LMD software was planned for implementation. This path offers an integrated solution, which enables STL pre-processing as well as part post-processing (slicing and tool path calculation), however being a work-in-progress, as of writing of this report.

5.3. New Platform Development

a) Proposed Concept

After several proposed concepts for the final LMD system, several features were defined for integration on the final product:

- Due to the large size of the machine bed (3 x 1,5 m), the final system should include a dual table configuration. This would enable parallel work jobs, which contribute to increased machine productivity, while still allowing large build volumes (with a work area of approximately 1,5 x 1,5 m), with a more cubical shape (which follows the current market demand for balanced dimensions) – visible on figure 57.

- Rotation motion would be a necessity for the final machine, since it provides increased versatility. Three different concepts were considered, which could be combined or used separately:
    - Installation of a dedicated rotating axis (for tubular or rotating parts in general, ideal for tubular coating and deposition), which increases the number of movement axis from 3 to 4;
    - Tilting/rotating table (which would be a completely new solution for the machine, enabling 4 to 5 movement axis);
    - A tilting head, which it would require a new nozzle solution (as explained before).
- Easy adaptation of the system for both metallic deposition and laser cutting operations (by changing the correspondent nozzle and using the same laser head).
- Part removal system, which may include sliding tables (similar to the current solution for sheet metal laser cutting) for facilitating part accessibility.
- Increased build rate envelope, with deposition rates up to 1 kg/h, for high-speed LMD processing;
- High versatility: ground-up production capability, part repair and surface treatment, backed up by great metallic powder compatibility (different metallic alloys).

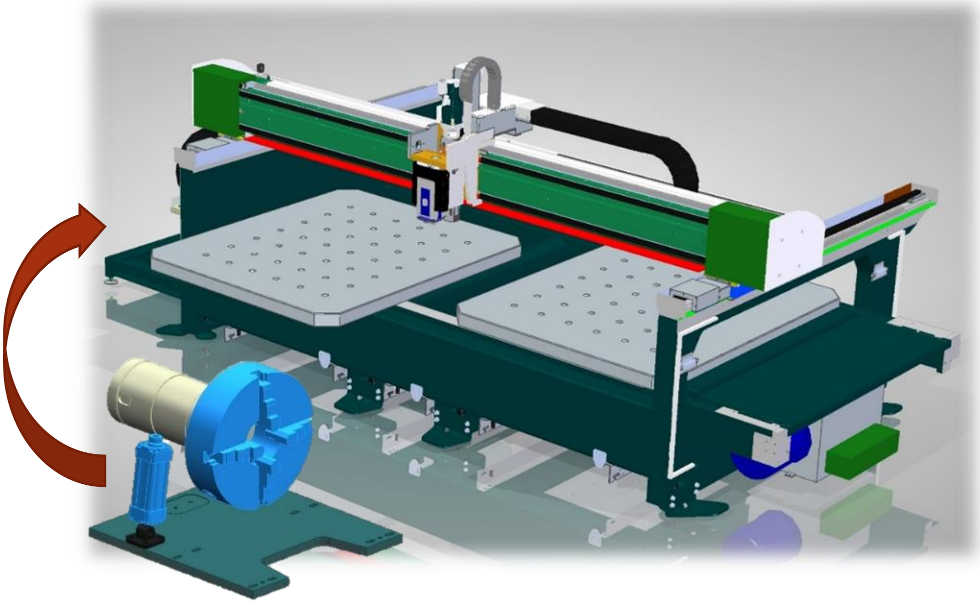


Figure 57 - Conceptual design of a dual-table layout for the final LMD system with a possible additional rotating axis for tubular and round parts.

6. SLM System Project

The SLM project was a parallel development for ADIRA’s planned AM machine range. The considered base platform for this assignment was the same as for the LMD system (previously described in section 5.1). The validation platform would also be common to the LMD project, as described on the next chapter.

The development process would focus on the capability of exchanging modules between the final systems which will compose the AM range, promoting a close relationship between both systems. The base platform would be shared and for simplifying component production, shared parts were also given priority. This increases standardization and simplifies production of these new systems.

For this endeavour, contribution from a laser technology institute was invaluable, collaborating with their know-how for the base concept and initial development. The preliminary testing was also conducted at their premises; thus concept implementation was made in-house. Fig. 58 shows the main stages of this development process.

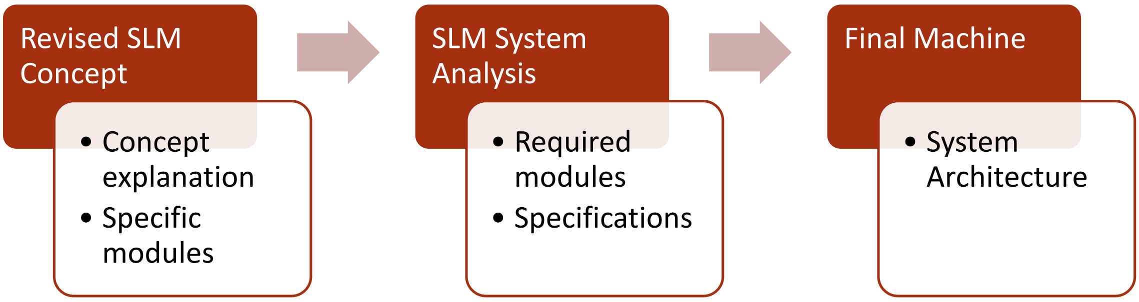


Figure 58 - Discussed topics within the SLM system section.

6.1. The Revised SLM Concept

a) Main Objective

ADIRA’s main goal is to innovate within the predeveloped AM productive methods, creating the possibility to manufacture large metallic parts and to create a machine with a more production-oriented design, matching the existing trends for AM mass production.

With this in mind, the SLM concept as it is currently known should be revised and adapted to the proposed objectives. Therefore, the traditional closed chamber design would have to be discarded in favour of an open design since this was a requirement for adapting the current machine platform and because it would better suit the proposed mass production criteria. The initial conceptual design was based on a modular SLM process chamber.

b) Proposed Concept

This concept would focus all process stages within a small-scale process chamber, attached to the machine gantry system. This modular chamber would then be moved across the powder bed surface, selectively processing different segments throughout the part development procedure. The SLM module would include all necessary laser components for scanning the powder bed surface and melting the metallic powder as well as the gas supply components that would maintain a semi-controlled atmosphere inside the chamber. It follows a completely modular concept, allowing it to be installed on the original machine gantry system.

Although innovative and interesting, this concept presented some important risks, such as not being completely gas insulated (which could present some processing issues, related to part distortion or oxidation, as well as high gas consumption due to the open space between the chamber and the powder bed surface). Additionally, some concerns had been considered in relation with disturbances on the powder distribution due to the movement of this module and the associated pressure gradients.

6.2. SLM Specific Modules

a) The SLM Modular Chamber

In order to make it possible to introduce the new open chamber design concept, a modular chamber had to be developed (figure 59). This component would be integrated into the existing gantry system, similar to the regular laser-cutting process head of the current ADIRA systems, although with a completely different working principle. This module includes:

- Chamber enclosure with the necessary laser safety measures;
- Laser optical components attached including collimator, focusing and scanning unit;
- Gas circulation capability through intake and exhaust units (described next);
- Atmosphere measuring points for controlling process conditions.

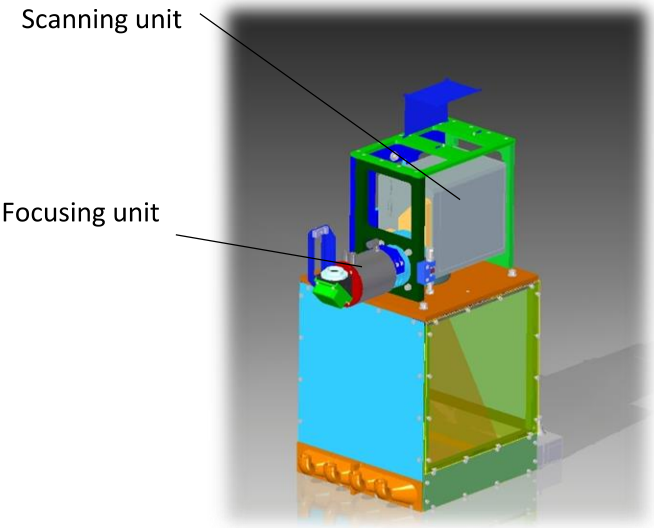


Figure 59 - CAD model of the modular SLM chamber.

Movement of the modular chamber is guaranteed by the existing machine gantry system, which positions it over the powder bed for laser processing. After processing the area, it is dislocated to another part of the surface and the procedure repeats itself. Therefore, the powder surface is divided into smaller areas, like tiles on a chessboard. Part placement and slicing must take this into account, hence creating a new pre-processing feature which was designated as tiling. For continuous parts this must consider the possible interface between adjacent tiles and additional process techniques must be considered (such as intermediate scanning vectors, for example).

In order to maintain an adequate process atmosphere, this modular chamber must assure a constant flow of argon gas near the powder bed surface (where the laser processing action is occurring). With this in mind, intake and exhaust units are attached to the chamber near its base, thus providing the necessary gas circulation, in order to renovate this localized atmosphere.

For ensuring the gas circulation, a pump and filter (for filtering exhaust burn-off products) would need to be applied into the circuit, with an additional argon source connected, to guarantee that an inert atmosphere is maintained.

b) Laser Source

For the SLM process, a suitable laser source had to be selected. Lower laser power is used since the amount of heat necessary for melting the powder layer is not as much as for laser-cutting, for example. The spot size is smaller and heat transfer is therefore lower, hence not requiring as much power. On the other hand, laser spot size must be small enough in order to increase precision and make it possible to produce very fine details.

c) Powder Supply System

The powder supply system was developed as a custom solution for a large machine, although with similar principles that can be found in other SLM machines. This part of the project must contemplate storage capability, powder distribution and lay-up in the powder bed area and further processing of overflow and unused material. With this in mind, these several features were implemented, following the indications provided in a preliminary concept study [55].

As large metallic parts require large amounts of metallic powder, a concept for a large external powder storage was developed. After beginning the SLM process, the material would be transported into the supplying unit, which contains two critical components: the screw conveyor and the spline shaft (as seen of figure 60). The first one guarantees that the powder is evenly distributed along the width of the powder supply unit, avoiding that excess material is deposited on a certain area of the powder bed. The second component is responsible for regulating the amount of metallic powder that is fed into the build platform (the grooves of the shaft are filled and the powder is supplied depending on the rotating motion of this part).

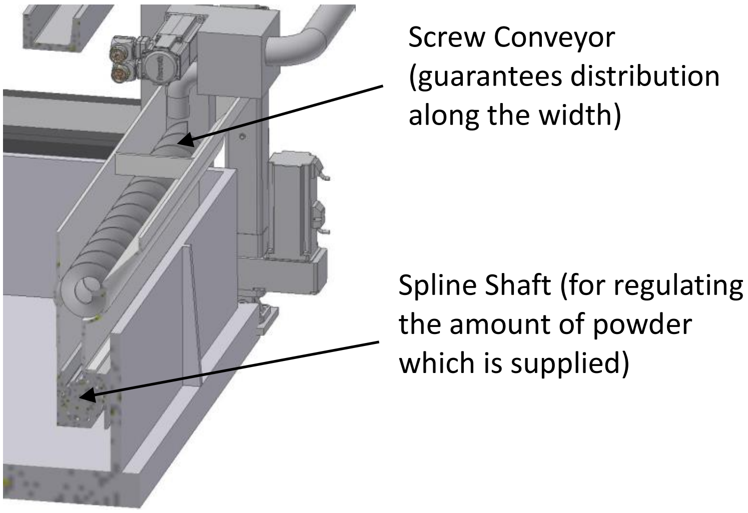


Figure 60 - The powder supply unit (preliminary concept) [55].

After powder is delivered to the building area, a suitable application device would have to be designed, in order to level the powder layer for the laser scanning procedure. For this a carbon brush, silicone lip or a metal blade may be used for distributing the powder layer. In figure 61, it is possible to further understand the powder delivery to the machine work area and further distribution, by using a carbon brush. These concepts are based on existing market solutions, from established SLM machine developers [55].

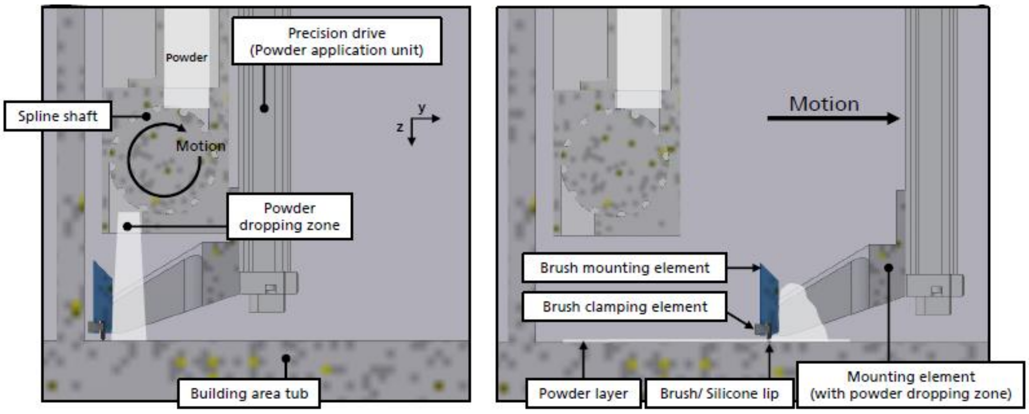


Figure 61 - Powder delivery by rotating the spline shaft. The grooves are filled with powder and regulate the amount supplied (left). Next, the powder must be distributed as a new layer, by using a carbon brush (right) [55].

d) Modular Powder Bed

With economic and environmental sustainability in mind, the ability to reduce the amount of material necessary for a build job is considered of great interest, especially considering the vast amount needed to process a big powder bed. Several concepts for a modular powder bed were discussed, with the objective of designing a system that would be scalable and resizable, allowing for a reduction of the build volume when possible.

Since the SLM process consists on lowering a build platform and depositing a new layer on top of the previous one, a direct approach to this matter would be to create a segmented building platform, which enables the lowering procedure for the whole structure or only parts of it. This way, when a smaller building space is needed, only part of the platform is lowered and the remaining stays on top (reducing the used volume and thus the necessary powder material).

A raw concept is presented next:

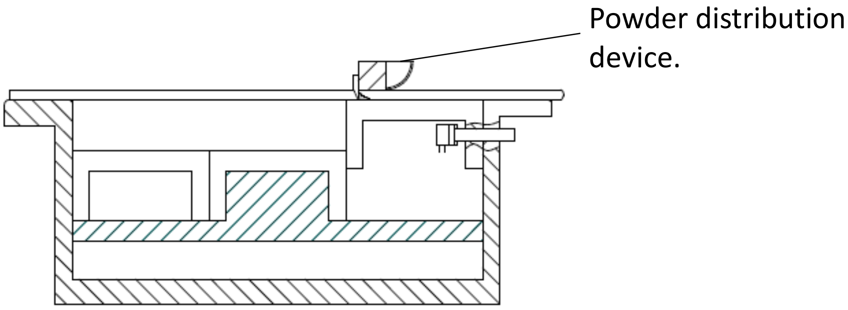


Figure 62 - 2D concept drawing of a possible modular chamber concept. Vertical actuation is placed in the middle and the remaining processing area can be fixed independently.

In the previous concept, the vertical movement of the table would be executed on only one of the modular areas (the middle one). The remaining areas would have a simultaneous movement, caused by the same actuating structure. In case of only needing a partial building volume, a fixation system would be used to couple the platform to the wall of the powder bed, therefore not allowing it to lower with the rest of the vertically moving platform.

This concept is a possible solution for the matter at hand, although not being developed within the scope of this thesis. Nevertheless, it is being planned for future developments (possibly for the final system to be produced by next year).

e) Software

Similar to the LMD machine project, a software suite would have to be implemented for the SLM process, as well. In this case, a more standardized solution was chosen, following the current market trend for AM pre-processing in PBF processes. This software would assure the production of metallic support structures and all the necessary functions for preparing the STL part files, in order to obtain successful process results.

For post-processing operations, such as slicing, process parameter definition and machine communication, a special Build Processor will need to be developed, allowing high compatibility with the pre-processing software suite. Additionally, since ADIRA’s machine concept includes a special design, with a tiling concept (segmented processing of the powder bed by a modular process chamber), exclusive functions would have to be implemented.

7. AM Demonstration System

7.1. Project Objectives

As a means to demonstrate the new ADIRA AM portfolio, a demonstration system was planned for unveiling by the end of October 2016. This system would include a dual table configuration, like the final LMD machine concept previously discussed, with a dedicated table for metal deposition and sheet metal cutting. However, instead of having a second table for DED processing, it was decided that a small powder bed structure should be included, this way allowing SLM operations. Summing up, the demonstration system would include three different processing capabilities: sheet metal cutting, metal deposition (LMD) and powder bed fusion processing (SLM).

The main advantages of this approach would be:

- Better promotion of the ADIRA AM portfolio (by including the different processes);
- Smaller work areas for both LMD and SLM would make it easier to implement the process in time for public unveiling, as well as process development;
- Smaller powder bed system implies less powder costs and easier material processing;
- Unique solution at the time, which makes this system an innovative, one of a kind product;
- Existing time and material resources are put to good use, since the platform would be taken from the existing BL 1530 and the project would be centred on implementing the AM processes with as less adaptations as possible.

For this solution to work, the same gantry system from the laser-cutting platform would be used, with two processing units installed (one for laser cutting/LMD and another with the modular SLM chamber). Machine structural adaptations would be avoided, in order to reduce project complexity and increase cost efficiency (by reusing already developed components). It should be noted that the use of an existing system and the short implementation time-frame limits the freedom of development. Therefore, although the objective is a fully functional prototype system, it still remains an experimental solution and not a final machine.

Both LMD and SLM process validations would be carried out in this machine, in a more small-scale approach. The smaller SLM powder bed would be combined with a hybrid LMD/laser-cutting table, which itself serves as demonstration of the easy swapping capability of the LMD nozzle (that could be exchanged by a suitable cutting nozzle for the corresponding application). Report of this system development section will follow this sequence:

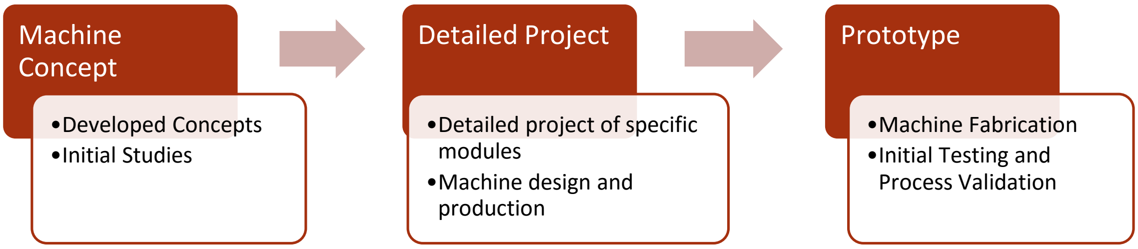


Figure 63 - AM Demonstration system workflow.

7.2. Machine Concept Development

As a first step for developing this system, a conceptual modelling was performed, on top of the original structure, in order to simulate the integration of the different components. These concepts were simply proposals of possible assembly configurations and were subject to discussion and further selection.

a) Dual head configuration

In order to include both LMD and SLM processes, each correspondent processing head would be included in the same gantry system (figure 64). This way, installation complexity could be reduced, although some necessary care should be taken when placing additional weight on the structure.

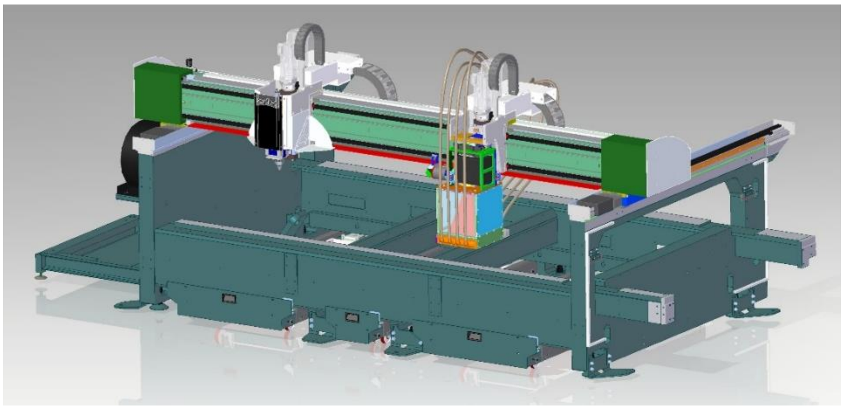


Figure 64 - Dual-head gantry configuration (LMD on the left, SLM on the right).

The original process head installation was replicated, on the same gantry, allowing for the dual-head configuration. However, for the SLM process, the cutting head was replaced by the SLM chamber, which required new modelling of the support structures. The additional gas supply and exhaustion connections for the chamber were also modelled.

Some weight calculations were also performed, in order to estimate the new load applied by the SLM chamber to the gantry. This estimation amounted to 30 kg by summing up the optical components weight (consulting manufacturer information) and considering an aluminium structure for the chamber. A preliminary FEM analysis was conducted on a prototype structure, in order to estimate relevant deformation (figure 65).

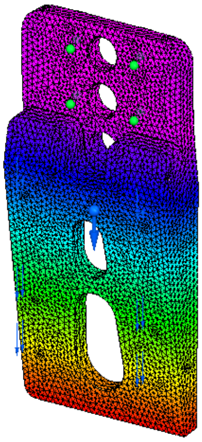


Figure 65 - FEM analysis of the modular chamber gantry support, in order to determine deformation due to the additional weight.

b) SLM Powder Processing Concept

For the SLM process, it was necessary to propose a concept for implementing this process within the machine. This would need to consider the powder bed structure itself (which would amount to about half the available machine processing area), as well as powder storage, application method and waste collection.

For the powder bed structure, this would be supported by the original machine side structure and central support beams (figure 66). Additionally, aside from the vertical movement of the build platform (for layer deposition), two linear movement axis were placed for the powder application module, in order to allow its travel along the powder bed length. The powder supply unit (on the right hand side of the machine) would include the described concepts on section 6.2c of this report.

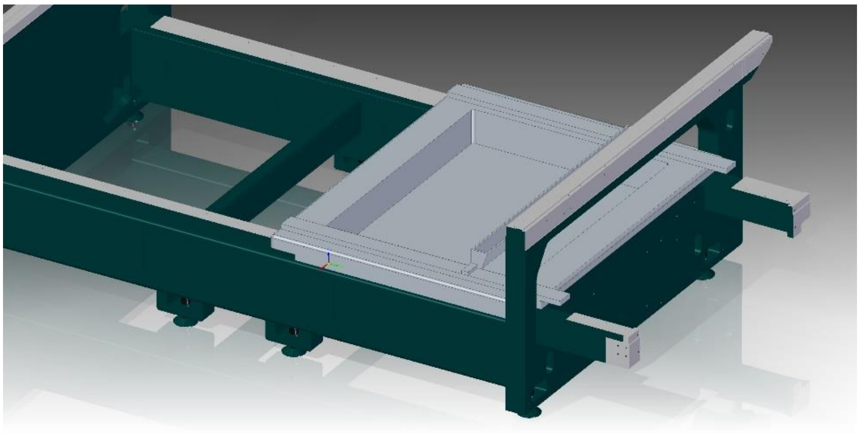


Figure 66 - Conceptual modelling of the powder bed area (about 1000x1200 mm area).

In order to maximize the usage of the existing space on the platform, the powder storage and overflow collection are placed on the same side of the machine, with a vertical disposition (as seen on figure 67).

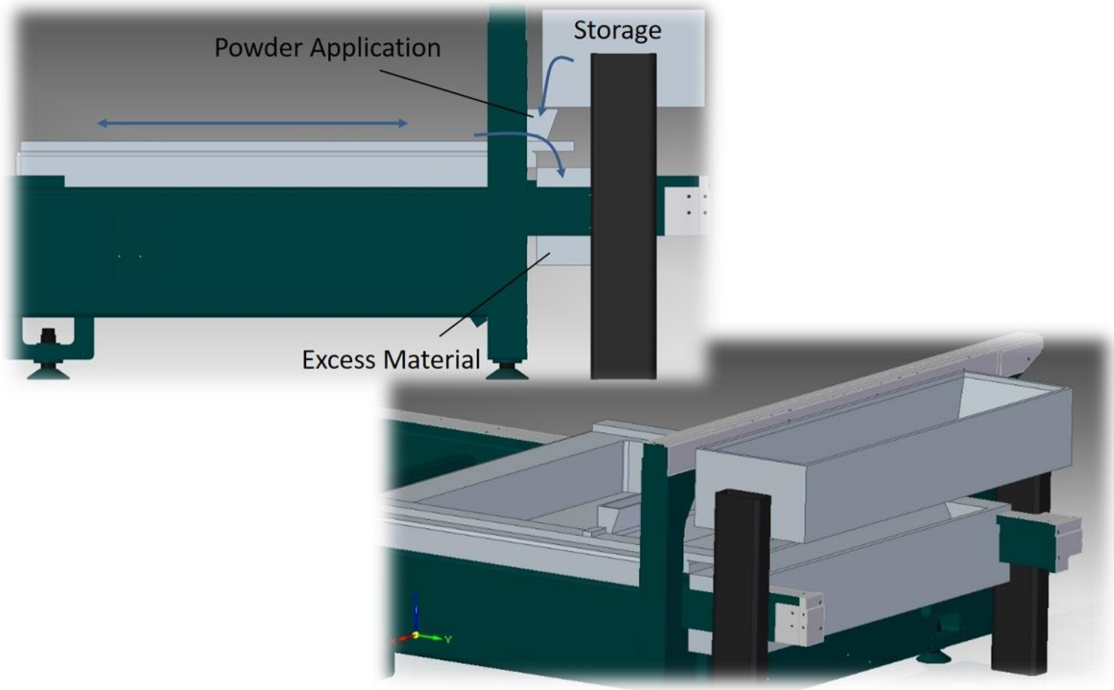


Figure 67 - Positioning of the different powder delivery and storage modules.

The powder processing cycle would be executed by the following operations:

1. Movement of the powder application module to the right, below the storage unit (as seen on the first image from figure 67);
2. Filling of the application module by opening the storage;
3. Movement of the unit to the left side of the PB;
4. The application unit will then lay down the powder layer by moving right and using a mounted brush to guarantee the correct layer thickness.

Correct powder dosage on both storage and application units would be guaranteed by adequate precision spline shaft conveyors (as described on section 6.2). With this configuration, the powder material would be kept out of the inside of the machine, being directly accessible from the right hand side (both storage and overflow container), which would make maintenance easier and avoid possible contact with the internal mechanical components.

c) LMD/Laser Cutting Table

On the other half of the machine, the objective would be the implementation of the LMD process, with the possibility of laser cutting sheet metal (figure 68). The dual process feature would serve a demonstration purpose of the retrofitting capability of the LMD nozzle. The developed concept was based on existing laser-cutting hybrid tables, which combine the sheet metal support slats with a part support structure, which can be adapted and removed, if needed. Development was focused on using existing parts from the current laser-cutting table, in order to avoid the need to produce new ones.

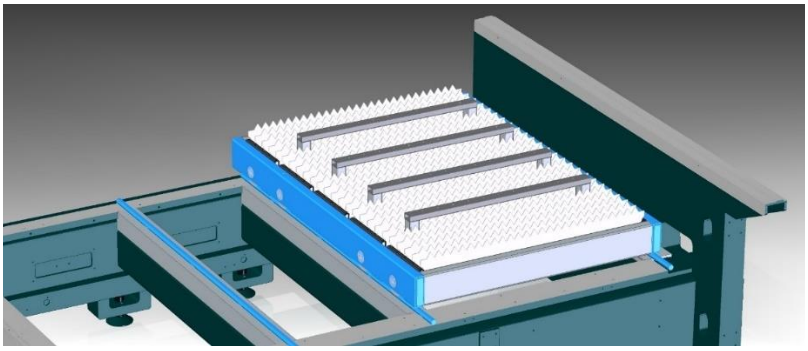


Figure 68 - First conceptual hybrid LMD table.

The slats would serve the purpose of supporting sheet metal for cutting operations and the support beams, placed between them, would allow the fixation of a support structure for a specific part, for deposition operations. These could be easily removed in order to allow the placement of sheet metal.

This hybrid table concept served as a starting point for the development of the final solution (described on section 7.3) although being quite different from the modular concept which will be proposed further on. Nevertheless, the main features and objectives from the initial concept were kept for implementation on the final version.

An important difference with the proposed system would be the direction in which the table would slide, perpendicular to the existing BL 1530 laser-cutting machine. This way, the worktable would exit through the front of the system, instead of the side, like in the original system, implying changes to the original machine coverage.

It should be noted that a separate study was also performed for a dedicated LMD table, without the possibility of including laser-cutting supports. This concept was discarded as it didn’t serve the purposes of the demonstration system, being less versatile. However, further application can be found on the future LMD-dedicated machine. The main difference to the hybrid table is the inclusion of a fixture surface (such as a clamping pallet) with the corresponding holes to attach clamps or other fixing elements, while using a similar frame (figure 69).

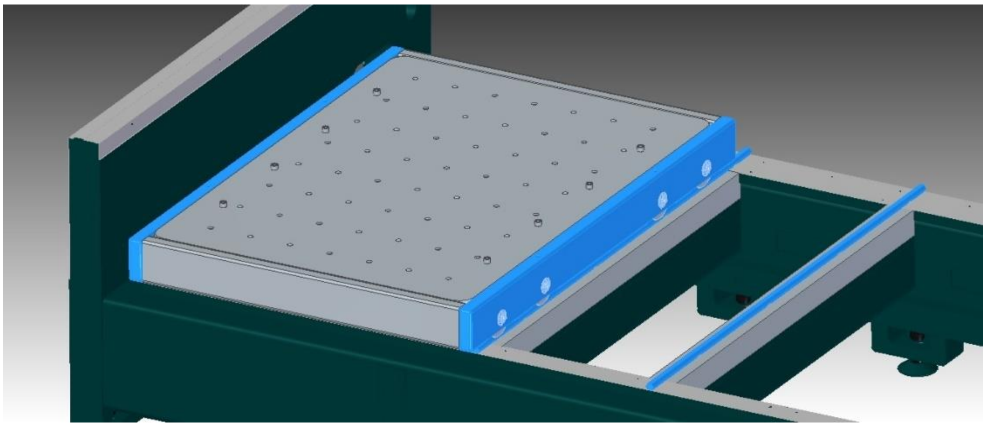


Figure 69 - Dedicated LMD table concept.

Fixing elements may be standard solutions from suppliers such as Elesa Ganter. Nevertheless, specific part fixation elements may be designed for more complex shapes (figure 70).

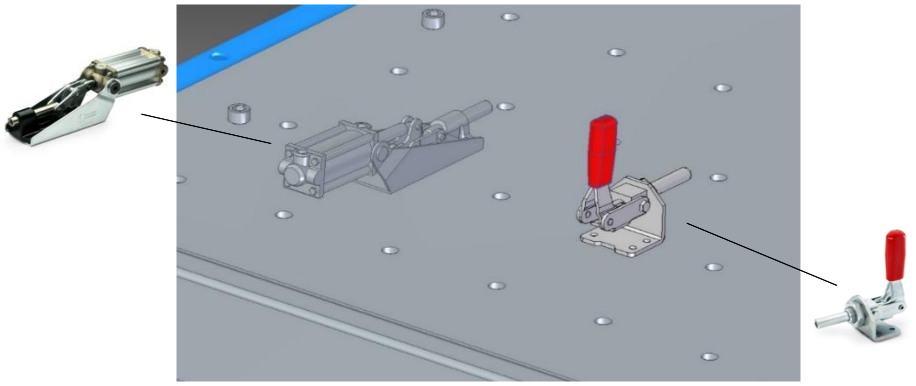


Figure 70 - Part fixation solutions from Elesa Ganter: GN 890 pneumatic solution (left) and mechanical alternative GN 843.1 (right).

d) Exhaustion System

For this new machine, a different exhaustion system had to be considered, changing the solution originally adopted for the laser cutting system. Since the SLM process would be executed within the modular processing chamber, local gas supply and exhaustion would be employed. Therefore, the main concern would be the LMD process exhaustion.

For the conventional laser cutting process, the exhaustion was performed on the lower part of the structure, since the process gases were oriented downward, such as the removed material. However, for the LMD process, since process fumes tend to dissipate in a less oriented manner (especially when more than 3 axes are used for rotational trajectories) and powder material may scatter around the worktable, a superior exhaustion system was considered (figure 71). This application is similar to the ones used with 3D laser-cutting robotic systems.

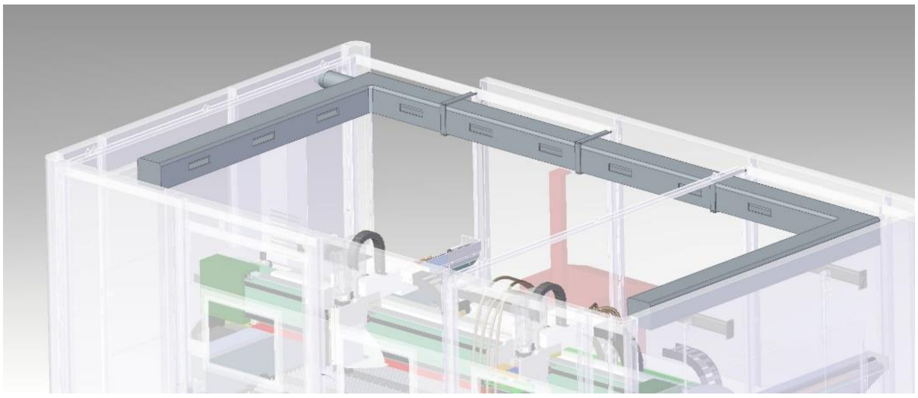


Figure 71 - Superior exhaustion system concept, with dedicated supports fixed to the original machine coverage.

This concept was discarded since it would increase system production and assembly complexity (introducing important changes to the original machine). As time-to-market is a critical factor, it was decided that for the demonstration system, the original inferior exhaustion system would be kept (only half of the system is needed, since it will only be implemented for the LMD half of the platform area).

e) LMD Powder Feeding

Powder feeding for the LMD process will be ensured by the previously described powder feeder. This peripheral equipment was placed behind the LMD table, at the back of the machine (figure 72). The powder lines would then traverse the exterior coverage, pass through a support on the top of the machine and come down directly into the powder nozzle. This way, shorter cables would be used, with a smaller path length, which is a critical factor, since powder feeding rates are increasingly difficult to stabilize with long powder lines (more reaction time, less responsive system).

The powder flow would be directed to a dedicated splitter, and after being separated into three, would be introduced into the three-jet nozzle:

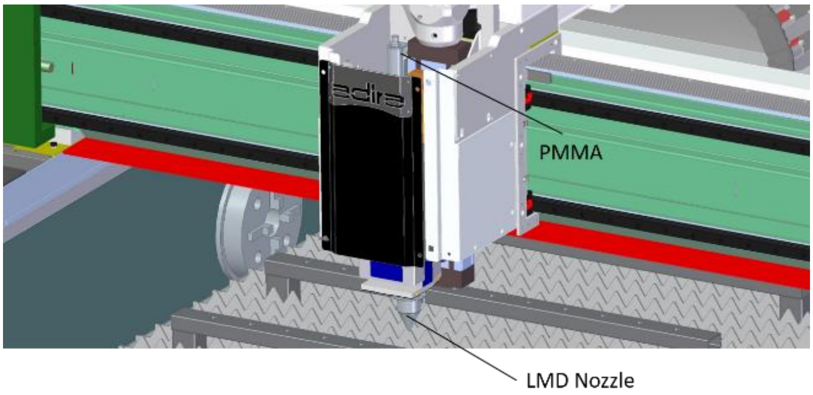


Figure 72 - Modelling and installation of the LMD nozzle and PMMA powder splitter.

f) Rotation Axis

An additional LMD-specific concept that was studied was the possibility to integrate an additional rotation axis, for tubular or revolution-shaped parts processing. This concept could be included for the LMD process in two different ways: either placing the part fixation elements on the machine structure (figure 73) or by using a simpler peripheral approach (with an external element capable of being fixed to the table itself – figure 74).

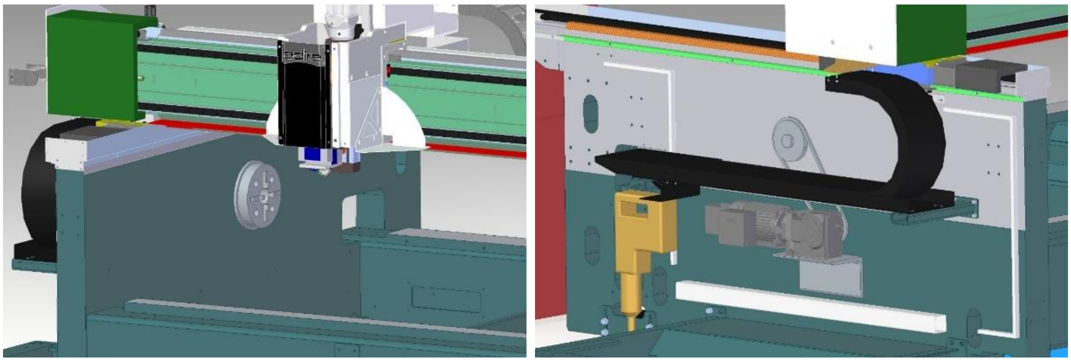


Figure 73 - Integrated rotation axis concept, with an external motorized system.

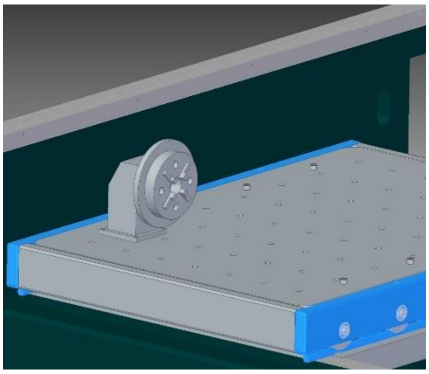


Figure 74 - Modular rotation axis approach.

For the first option, a motorized rotation axis would be incorporated to the side structure, with the motor and transmission on the exterior side. The second concept would be easier to implement, by using a standard solution (robotic peripheral equipment). Nevertheless, a good fixation to the platform is a necessity and the motorized equipment must be correctly connected to the machine command.

It was decided that the additional axis would not be included in the demonstration system, due to the increased complexity of the overall configuration, although it is included in the final LMD system objectives. These features are, therefore, being considered for the final system.

g) External coverage modifications

For accommodation of the additional components for the AM simulator system, the external coverage of the original machine would need to be modified. This involved an increase in machine length and different support structures for the original panels. For accessing both the main powder storage, as well as the overflow deposit, access doors should be installed on the side of the machine coverage (figure 75).

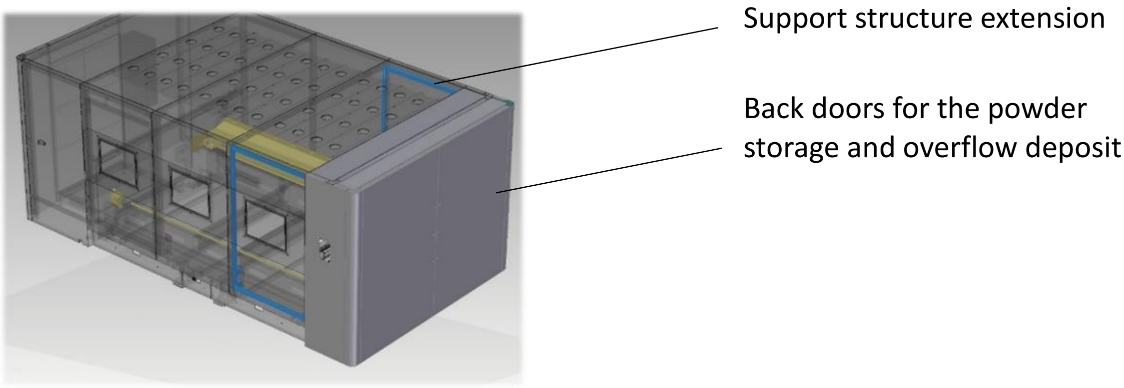


Figure 75 - Machine coverage extension, with changes to the original supports (in blue).

Furthermore, since two different processes would be included in this machine, suitable accessibility for both should be provided. With this in mind, the current door scheme would not be valid, as it only provides one door (at the left) for access to the laser-cutting table. It was proposed the installation of two larger sliding doors, each giving access to one of the processes. The sliding mechanism would be especially useful, as it doesn't interfere with a possible table support that may be used in front of the machine (for removing the LMD table, since it would come out of the front).

On the other hand, the larger doors would mean that they would occupy a great area in front of the machine for opening (figure 76). It was taken into account that this type of coverage panels are usually only supplied up to 1.5 metres in length, which imposes a limit on the size of the installed doors. This concept was proposed as the solution that should be implemented on the AM simulator, which would require a new design and colour scheme for this machine (both tasks were attributed to an external design studio).

Figure 76 - Conceptual representation of the exterior machine looks (subject to change until production).

7.3. Machine Project Development

After concept development, the machine project was started. As part of the team dedicated to this development, an important part of the produced work during this internship involved developing some of the composing modules of the final machine, which are described in detail throughout this section. Preferred welding processes are based on the MIG/MAG technology and the DIN 17100 standard was chosen to define the steel grades used for the production of the required parts.

a) Laser-cutting/LMD Hybrid Table

The work area for one of the processes to be demonstrated on the AM simulator (direct deposition) was developed with one main objective in mind: hybrid versatility. In order to validate the simplicity of exchanging between LMD and laser cutting operations, by changing the process head nozzle, a hybrid table had to be developed, which would be adapted to both processes. Moreover, the table dimensions would need to use up the available space, without compromising the SLM process to be developed and implemented in parallel.

Main Weldment Structure

The main table structure follows a similar assembly method of the existing ADIRA laser-cutting tables, using several already existing components and adapting others to the new requirements (thus reducing production complexity and time-to-market). The table is made out of several welded profiles:

- **Side profiles (figure 77):** made out of 150x50 mm section standard profiles, with 1710 mm length and 4 mm thickness. Corresponding machined sections allow for coupling the wheel assemblies for moving the table over a rail system. Superior holes are provided for fixing eye bolts (in order to allow lifting of the structure). These components are made from St37 steel (DIN 17100).

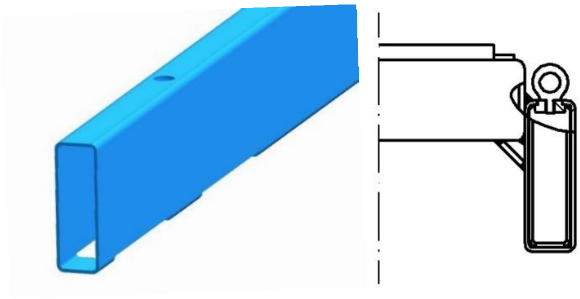


Figure 77 - Side profiles for the weldment structure (left) and eye bolt placement (right).

- **Top frame (figure 78):** with a rectangular 1710x1310 mm shape (external dimensions), made out of four St37.2 welded profiles (60x80 mm, 5 mm thickness along the width and 40x80, 5 mm thickness along the length). It has 2 L-shaped St33 steel profiles (25x25x5 mm) along its length, welded on either side of the frame. These profiles support the slat modules for the laser-cutting operations (described next). Additionally, machined and drilled surfaces were placed along the top of the frame bars, in order to provide a place for fixing a bar structure to support the LMD parts.

  For including these surfaces, 20 mm thickness metal sheet (St33) was used for the width of the table and 8 mm sheet was used along the length. These thicknesses have been selected based on the usual material that is used for ADIRA's machines and both components are machined afterwards to a height of 15 and 5 mm respectively (the height difference compensates the placement of the support crossbars, as seen next). M8 drill holes were placed with a 150 mm gap between them, along the machined surfaces (which are stitch welded with 50 mm long fillet weld beads to the top of the frame profiles). All weldment operations are performed using in-house MIG/MAG welding.

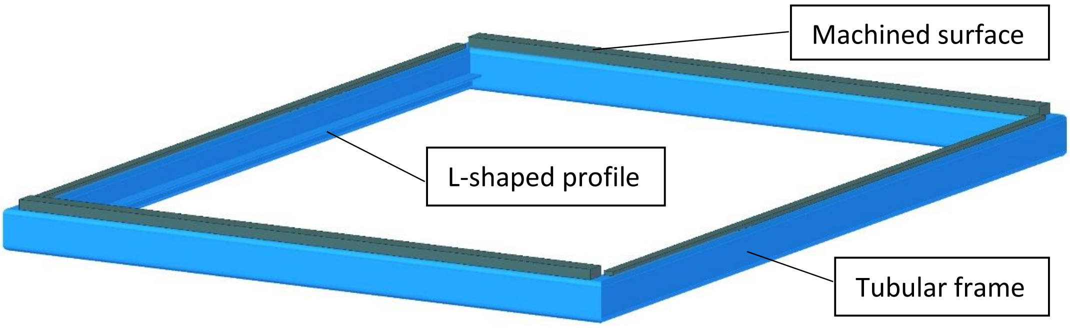


Figure 78 - Top frame structure with its main composing elements.

- **Eye bolt placement:** in order to successfully use eye bolt screws for lifting the structure, these would need to be connected to the side profiles (as previously explained). However, due to the small profile thickness, the hole thread length isn't enough for supporting the structural weight of the table. Therefore, bushings were spot welded to the side profiles with an adequate threaded hole for screwing the eye bolts. Four M8 eye bolts support a maximum weight of approximately 570 kg (according to the DIN 580 standard), therefore being enough to lift the entire welded structure with 118 kg [56].

- **Weldment assembly:** the top frame and side supports are connected by fillet stitch welding and by using an additional 6 mm thick St33 sheet metal support structure (see figure 79). For additional information on the weldment fabrication, extracts from the 2D drawings are present on annex A5.

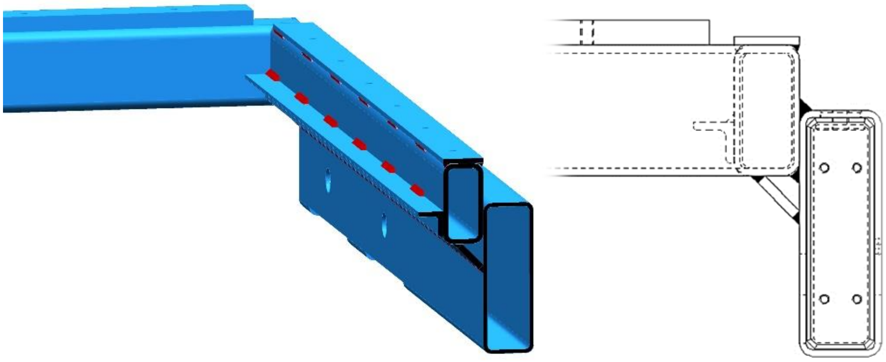


Figure 79 - Weldment assembly cut view, with the 6 mm thick support visible underneath. 4 threaded holes are produced on one of the ends of the side profiles, for fixing the LMD table on the rail system, as explained next (right).

Laser-cutting Slat Modules

In order to follow a modular design principle, the slats for the laser-cutting operations were incorporated into removable modules, which are supported on the L profiles from the main structure. These were assembled in a similar way as the top frame of the main structure:

- **Frame:** similar constructive principle of the table structure, with 50x50 mm section tubular elements, with a thickness of 5 mm. This frame contains four support points, which have welded bushings for screwing the eye bolts (just as in the main table weldment). This allows for removal and handling of the different slat modules. The tubular profiles along the width of the slat module have machined spaces for fitting the slats into place (3,3 mm width), allowing to fit 7 sheet metal support slats. This component is welded by MIG/MAG welding, similar to the machine structure frame.
- **Central supports:** two 8 mm thick sheet metal central supports are welded to the frame, for increasing rigidity and to provide additional support for the slats under load. These are made from RSt37-2 steel (DIN 17100).
- **Support combs:** they are fixed to the central supports, using M5 screws. These parts are made from sheet metal, cut and bent to shape and include 7 spaces for fitting and guiding the slats, just as the frame. These are produced by laser-cutting and posterior bending operations, from 3 mm thick sheet metal. Once again, RSt37-2 steel was used.

- **Slat structures:** these were based on the original components from the laser-cutting system, being shorter, in order to be adapted to the smaller length of the slat modules (figure 80). They have 3 mm thickness and are laser cut. Due to the small thickness, these are made from RSt37-2 graded steel.

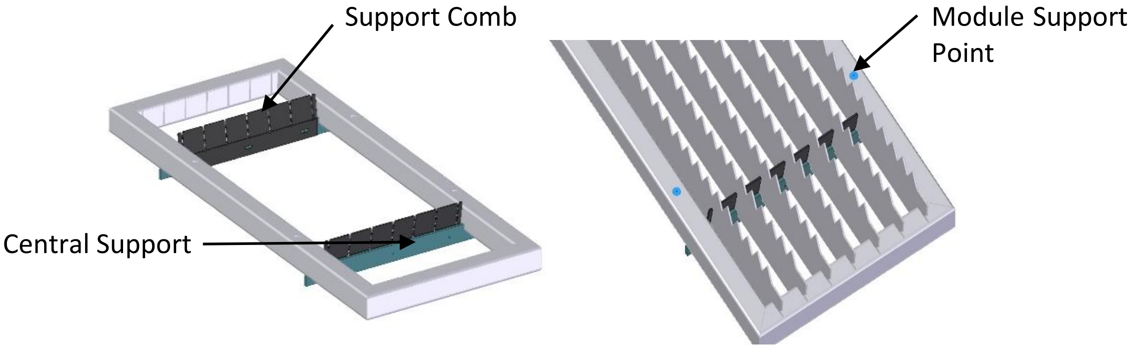


Figure 80 - 3D CAD visualization of the slat modules.

To further clarify the fitting of the slat components into the module, a 2D cut view was produced (figure 81), with these parts and the correspondent supports:

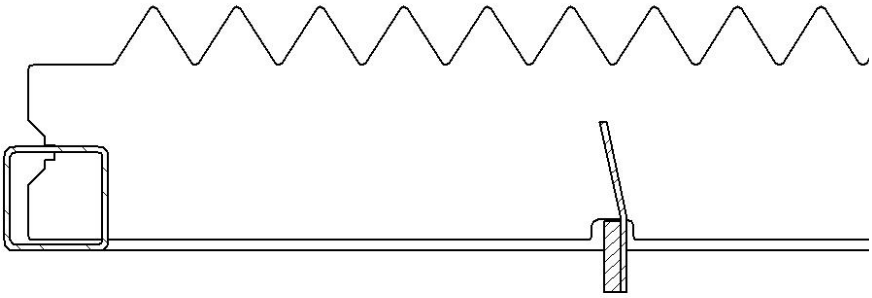


Figure 81 - 2D CAD cut detail of the slat support.

To further clarify the slat module assembly, additional exploded views are available in annex A6, as well as the detailed drawing for the slat itself (a part produced by laser-cutting, due to the complexity of the required contours and amount of dimensional information).

Final Assembly

For the final table assembly, several configurations may be used. Since a modular concept was applied, the end-user may choose how to assemble the structure, according to the required end result (hybrid application, only LMD or only sheet metal laser cutting). This is possible since up to three sheet metal modules (slat modules) may be placed on the machine in any desired position. It should be noted that the height of the slat modules installation was adjusted to match the original slat height of the laser-cutting table. Therefore, for laser-cutting operations, vertical travel would be the same of the original machine (standardizing both systems).

The LMD work area will be supported by specific crossbars, which may be placed along the length of the table, within 150 mm distance from each other (according to the screw holes along the sides of the welded structure). These are made from tubular profiles and a machined bar stitch welded on top (more details on the detailed drawing from annex A7). Additionally, up to three slat modules may be placed on the table for full laser-cutting operations or these may be combined with the LMD crossbars for hybrid operation.

For showing the table capabilities, a hybrid assembly was chosen. Two slat modules were placed on the table, along with an additional LMD crossbar (assembly details on annex A8). For the LMD operation, a 10 mm thick metal sheet was fixed on the table frame and LMD crossbar, as an example work area for LMD operations (figure 82).

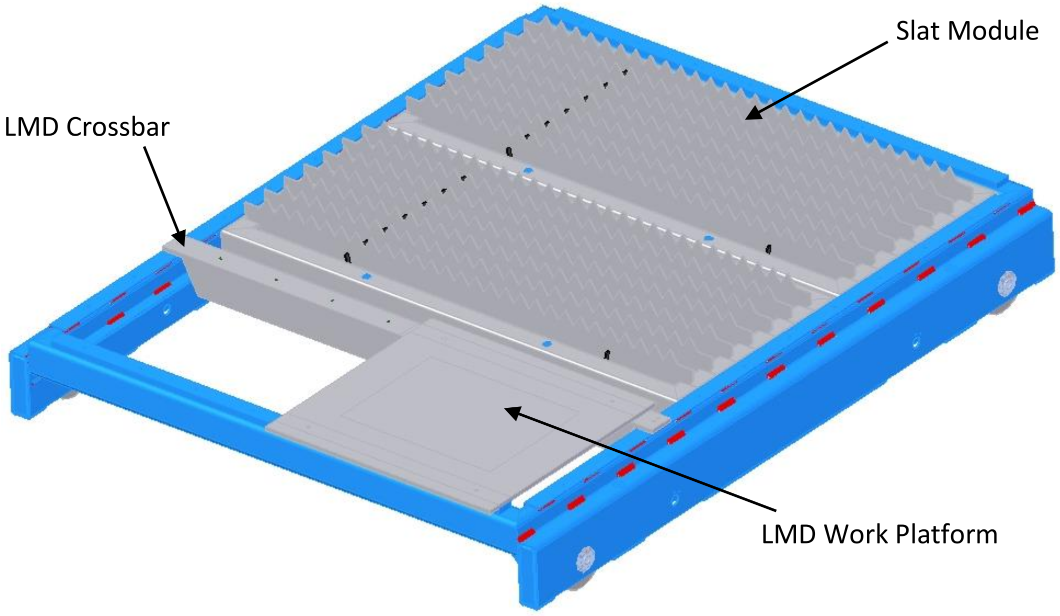


Figure 82 - Final assembly of the LMD hybrid table. Weld beads are coloured in red.

For a use-case scenario, an injection mould half part was placed on top of the LMD platform. This part was provided by a partner within the Portuguese mould industry, as a possible scenario for an LMD operation, based on surface coating for hardening the mould cut-off surface. This use-case was chosen taking into account the potential client necessities and the machine characteristics, being decided it was a suitable component to test the concept. Due to the great part dimensions and weight, stress testing was performed on the structure, using FEM analysis (as seen next), in order to determine if the deformation would compromise process precision (too much vertical strain may affect layer flatness and precision).

Additionally, four wheels are assembled to the structure, allowing the table to roll over rails that will be placed on the machine platform (supports described on the next section). The wheel assembly is based on an eccentric fixation, allowing for height calibration of the rolling element (exploded view from the assembly on annex A8). For more details on the table weldment and assembly, additional figures from the 2D production drawings are present on annex A5 and A8, respectively.

Structural Simulation

In order to have a perspective on the capability of the structure to withstand a hypothetical load under process conditions (especially relevant due to the objective of handling large metallic parts), some FEM structural simulations were performed on the critical components, using Siemens Simulation Express solution (NX Nastran solver).

The placement of a part for LMD processing may be made by using a metal sheet as a platform, supported by a LMD crossbar and the table frame. To simulate real-world applications, it was considered that a large 500 kg part would be placed over the metal sheet, which is supported on both the frame and LMD crossbar. This load is greatly exaggerated in comparison with the proposed end-user case (around 80 kg) with the purpose of increasing structural safety, as the parts for processing would most likely be lighter.

Using a 600 mm wide metal sheet as platform and considering the two support surfaces, the LMD crossbar was tested for half of the load (250 kg, 2450 N) distributed along the contact area with the metal sheet (as seen on figure 83). This approximation may provide a good idea of the structural performance, although not corresponding to the real life scenario. The load area was applied in the middle of the crossbar (as far away as possible from the lateral fixations, therefore simulating the worst case scenario).

In order to evaluate the structural performance, the vertical displacement was analysed and the maximum value calculated. The structure was fixed on its lateral screws and positioning pins.

It was considered that the desired limit would be 0.1 mm vertical displacement (100 micron), based on the current layer thicknesses that existing LMD machines provide (smallest benchmarked value). This way, the final support platform would not deform beyond the minimum proposed layer thickness, which was considered a good standard for evaluation, opening the possibility to implement this kind of process accuracy.

The results from the first analysis are presented next:

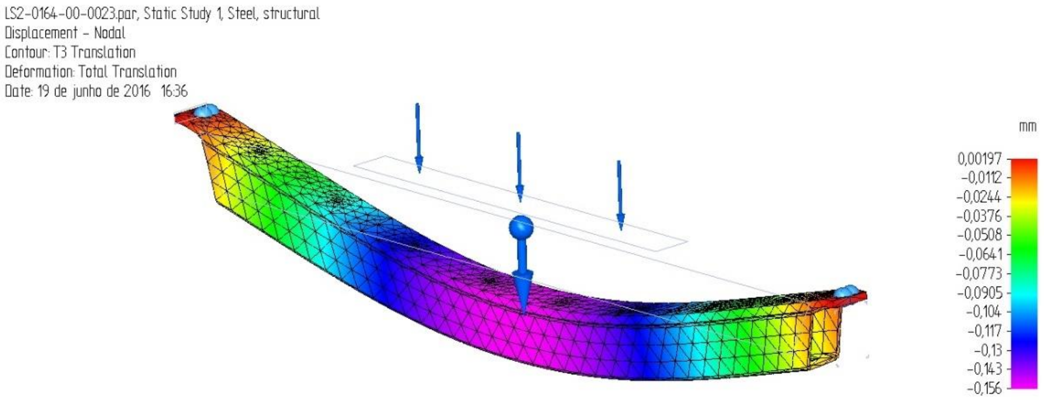


Figure 83 - LMD crossbar displacement FEM analysis. Distributed 250 kg load applied to the centre (marked rectangle) and gravity effect considered on the structure.

For this iteration, it was verified that a 0.156 mm vertical displacement had occurred. In order to minimise this value and make it admissible, two solutions may be considered: moving the load closer to the fixation points or placing additional LMD crossbars in the middle of the supporting platform. With the load distributed by 3 supports, and the load moved away from the centre, the results are more favourable.

With these conditions, a maximum displacement of 0.081 mm was calculated, which demonstrates the structure potential for withstanding large loads (always dependent on how they are placed on the machine table). The resulting deformation is shown next:

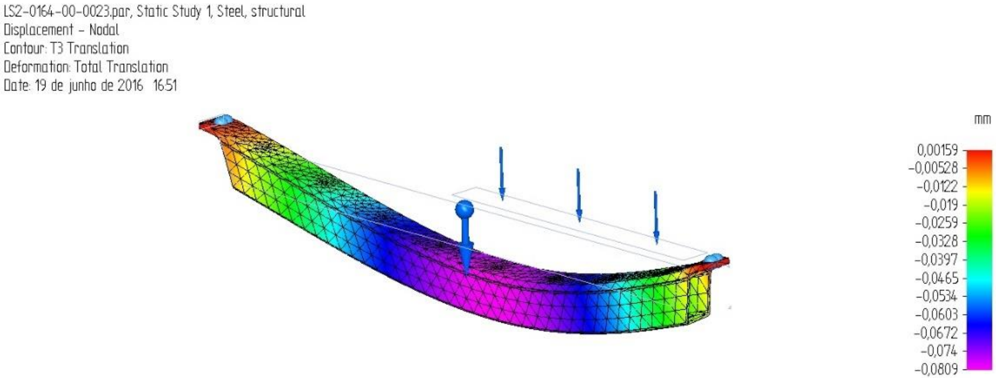


Figure 84 – Second LMD crossbar displacement FEM analysis. Distributed 166.67 kg load applied to the side of the structure (marked rectangle) and gravity effect considered.

The same situations were considered and the procedure was adopted for the lateral frame bar from the machine weldment structure. The first situation caused a maximum displacement of 0.121 mm and the second 0.056 mm, therefore it was concluded that the frame support bar isn't the critical component in this analysis:

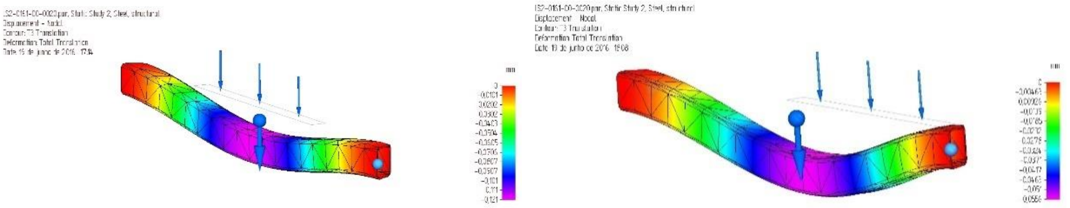


Figure 85 – Lateral LMD table frame bar testing: dual support with centre load (left) yields a maximum vertical displacement of 0.121 mm; dislocated load with three supports (right) originates 0.056 mm displacement.

Additionally, the 10 mm thick metal sheet was tested with the 500 kg load (applied to the center), considering three supports and the maximum value of the previously calculated displacements from the underneath supports (0.056 mm for the frame bar and 0.081 mm for both LMD crossbars) as an additional input to the simulation. The displacements are locked on the area of contact of the underneath structure and the metal sheet:

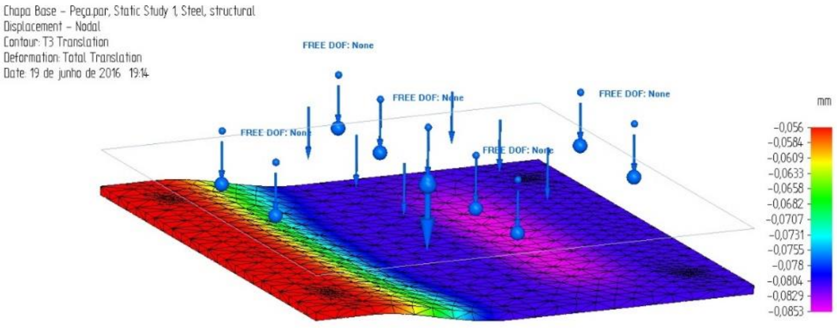


Figure 86 - Sheet metal FEM analysis considering maximum displacement on the underneath structures and a load of 500 kg.

The displacement on the left was blocked at 0.056 mm (due to the load conditions described previously) and the maximum value of 0.085 mm was verified between both LMD crossbars, as expected. This way, the registered values are accepted within the proposed objectives.

Structural steel was considered for all these parts and its properties for calculation were selected from the standard database provided with the simulation software.

b) LMD Table Installation

After designing the LMD table, its installation method would need to be defined within the machine platform. Since its placement is perpendicular to the original laser-cutting table, new supports had to be developed, keeping in mind that the original platform machine structure should not be modified. This was a strategic move in order to increase standardization and keep changes to a minimum. Therefore, besides screw holes for fixation of additional elements, further modifications of the platform were discarded (such as welding).

The table will have the possibility of being moved on top of rails (hence the four wheels assembled to the structure) and these are placed at a height of 630 mm (figure 88), allowing for the table to move exactly on top of the side structure of the original platform.

Two different structures were considered for each side of the table:

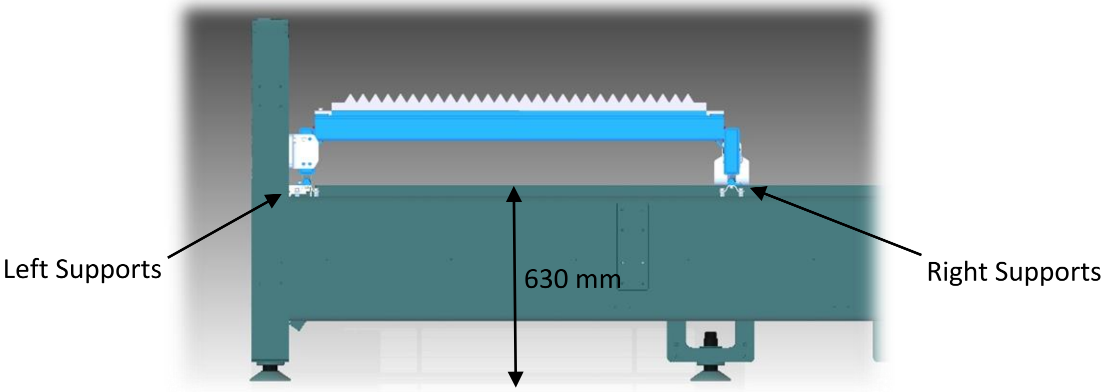


Figure 87 - Front view of the machine with the mounted table.

Left Supports

The left support structures are placed on one of the main structural walls of the machine platform. A standard UPE 100 profile was installed on the machine platform wall, by using 12 M10 screws and, in order to guarantee flatness precision for the table rails, a machined 20 mm thick metal bar was welded on top. This metal bar defines the table height (matching the original value of the laser-cutting system - figure 89). The U profiles are made from St33 steel and the top metal bars are produced from 25 mm thick RSt37-2 sheet metal.

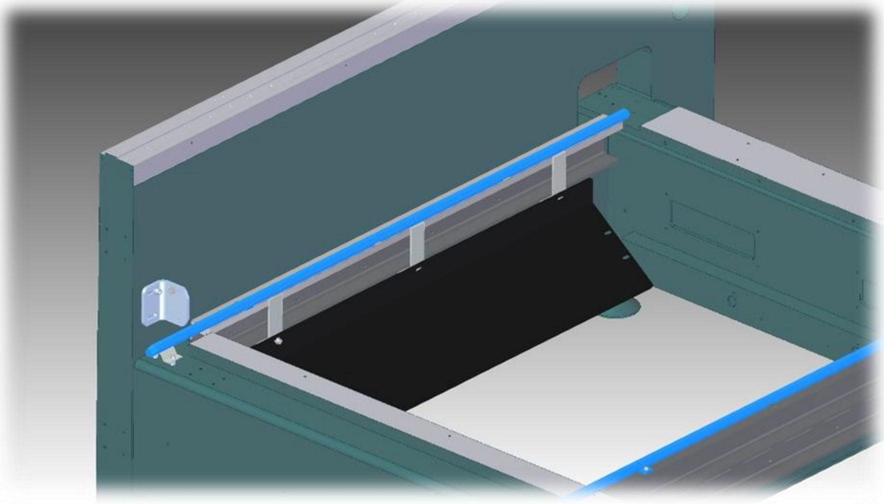


Figure 88 - Left support structures for the LMD table.

In order to level the rail and pass it over the front structure of the machine, a dedicated rail levelling support was made from 3 mm thick bent sheet metal (figure 90). This support is fixed to the machine using M8 screws and its height is adjusted by two M8 nuts underneath. It is also fixed to the rail by a M6 screw (from below). RST37-2 steel is used as the base material.

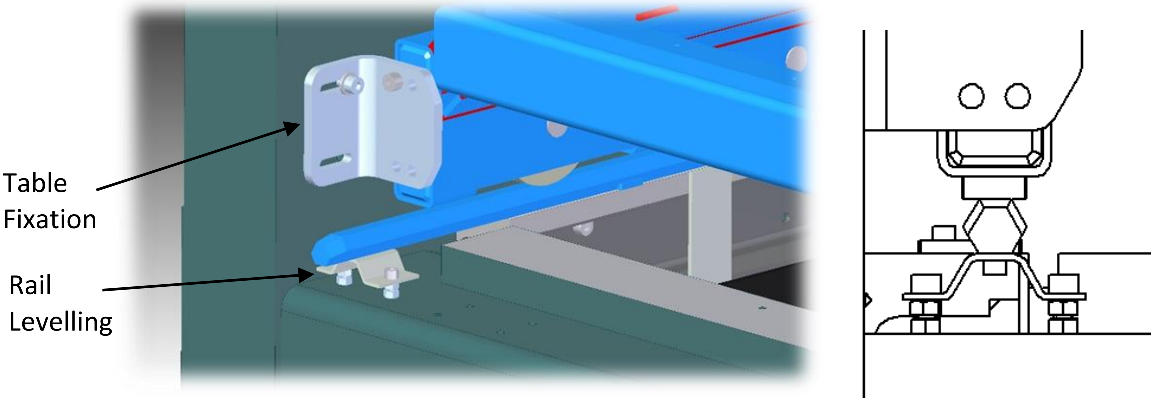


Figure 89 – Table fixation (left) and detail view of the rail levelling support (right).

Additionally, as seen on figure 91, a support was produced with 10 mm laser cut and bent sheet metal, destined to be fixed by four screws to the corresponding threaded holes on the end of the machine welded structure (shown in the previous corresponding section). This way, the table can be fixed, avoiding its movement on the rails after positioning (for machine transportation, for example). This support should be removed, for applications which require the user to remove the table from the machine (through the front door).

The rails were positioned on top of the metal bar. Its fixation is provided by small positioning blocks placed underneath, which are fixed on both the rail and the support surface:

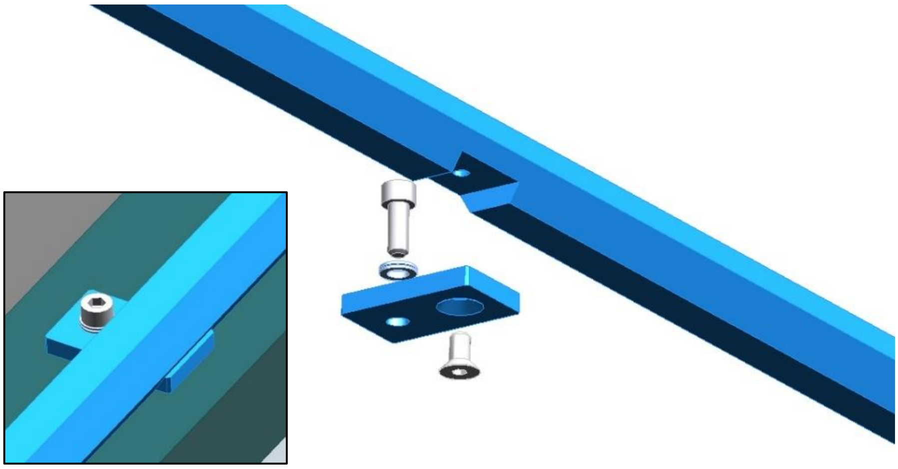


Figure 90 - Rail assembly method (exploded view).

Since the left supports would be placed on the previous location of some exhaustion system components from the original machine, dedicated sheet metal supports had to be designed. These would be welded to the UPE profile and would ensure that the location of the original exhaustion system deflectors would be exactly the same (same hole positioning for correct fitting). Detailed snapshots of these structures are shown next:

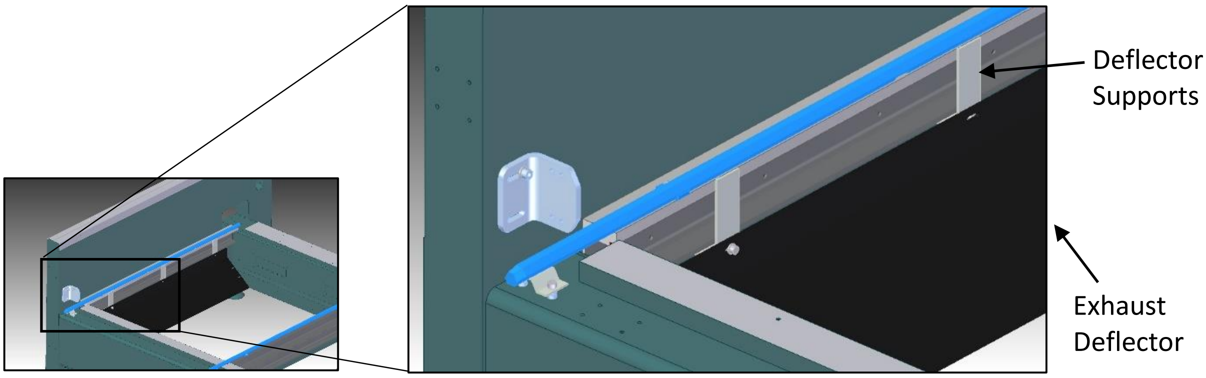


Figure 91 - Support structures for the exhaust deflector (in black). Three components are welded providing the threaded holes for fixation of the deflector (using M8 screws).

Further detailing of the left support structure is shown on annex A9.

Right Supports

For the other side of the LMD table, a similar approach was used. However, the available platform element for fixation was the middle reinforcement bars, which are placed at a lower height. Therefore, the type of support had to be adapted, although being based on the same solution.

Once again, the same UPE 100 standard profiles were used, although this time two are welded, one on top of the other. This is required since the one below is fixed to the machine platform central profile (again, by twelve M10 screws) and the one on top elevates the railing so the necessary height is achieved. Another rail levelling support is used on the front (same as for the left supports). Additionally, a rubber bumper and its correspondent support (fabrication similar to the table fixation from figure 92) is placed at the end of the railing, stopping the table at the back (figure 93).

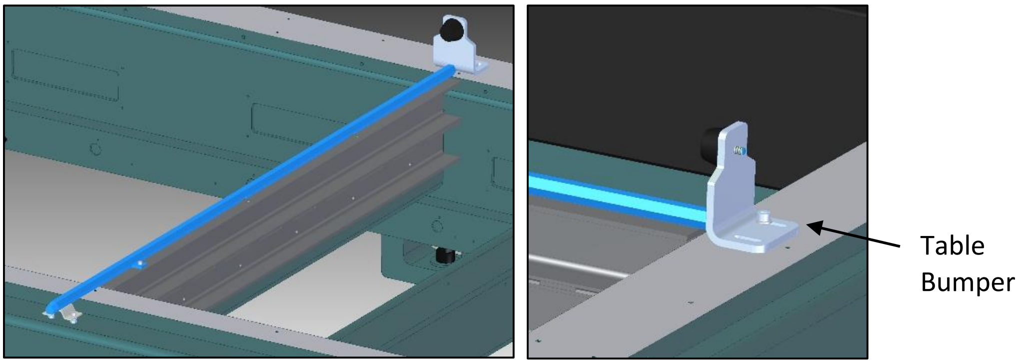


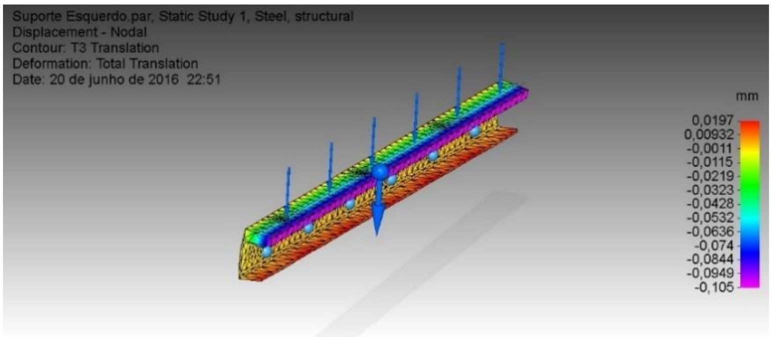
Figure 92 - Right support structures for the LMD table.

The 2D drawing is available on annex A10, allowing for a more detailed analysis.

Support Structure Load Simulation

In order to estimate the behaviour of both support structures under load (due to the placement of the LMD table), a FEM analysis was performed. It was estimated an approximate weight of 250 kg for the LMD hybrid table (CAD calculated), which by adding a 500 kg part (once again, a value beyond the likely application scenario), would amount to 750 kg. It was considered that the load would be distributed equally by the two supports, each supporting 375 kg.

The load would be distributed along the contact area of the rail with the underneath support (along with the gravity effect on the structure itself). The support fixation points would be the twelve screw locations where these modules are connected to the machine structure. Once again, a maximum displacement of 0.1 mm would be the desired value. The results are presented next: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Displacement - Nodal
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Deformation: Total Translation
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Figure 93 - Left support structure displacement FEM analysis. A maximum vertical strain of 0.105 mm was verified (the proposed deformation limit).

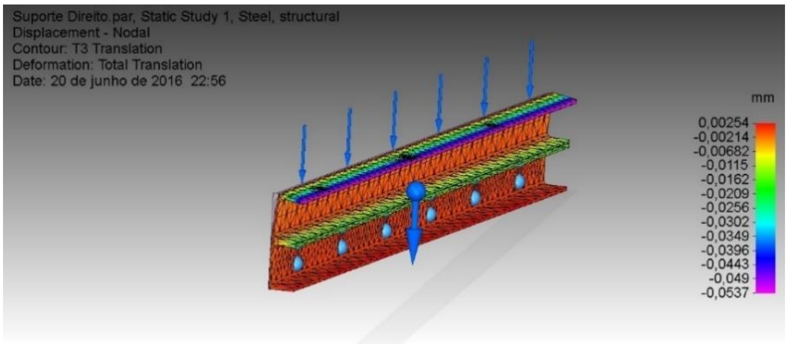

Figure 94 - Right support structure displacement FEM analysis. The maximum displacement was 0.054 mm (well under the proposed objective.

It was verified that the left support structure would be the critical element, showing a superior vertical displacement (its performance was very near the proposed reference value). A possible positioning of the part closer to the right support can be a good strategy to minimize vertical displacement, since the maximum support deformation would be reduced (moving away the load from the critical support). Nevertheless, it should be noted that these simulation conditions are contemplating heavy duty working conditions, which may not be planned for this initial machine and it was considered an equal load distribution between both supports.

Final Assembly

After creating the necessary support structures and adaptations on the machine platform, the LMD hybrid table may be placed on the machine (figure 96). Both supports were developed with the table width in mind, allowing for a correct fit of the structure inside the machine. The other half of the platform would be used for the SLM process.

As the table rolls on top of its corresponding rails, it was decided that for this experimental validation phase, its movement would be manual, without any mechanical solution, therefore simplifying assembly and development. In order to remove the table from the machine, an adequate external support will have to be produced, a matter to be solved on a separate project.

It should be noted that two different types of wheels have been used: the guide wheels (with grooves and a tighter fit on the rails) and the flat wheels (which can slide sideways over the rail). This allows the table to be placed more easily on top of the rails.

More information, views and 2D drawings from the LMD table installation can be found on annex A11, for further detailing of this section.

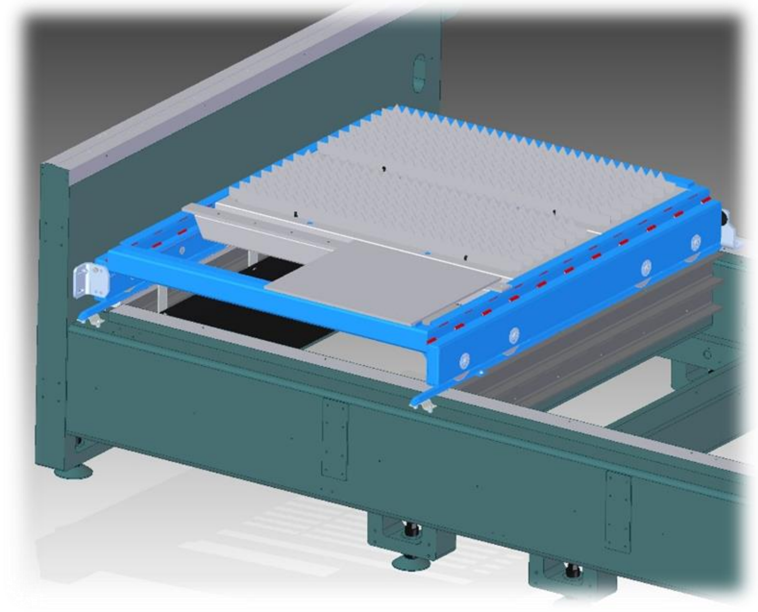

Figure 95 - Final LMD table placement on the machine platform.

7.4. SLM Experimental Work

During the project calendar, a visit to the Fraunhofer ILT facilities in Aachen was arranged, during the month of May, with the purpose of conducting some hands-on experimental activities with the SLM process. This included working with existing commercial systems, but more importantly, testing and processing work with the existing SLM modular chamber prototype.

Other additional activities have been developed, such as meetings with software experts from Fraunhofer ILT to define solutions for the command of the final system or with representatives from Materialise, in order to discuss AM software topics.

a) PBF Maintenance Operations

As a first step into the SLM world, knowledge of process-specific conditions and handling recommendations is essential. Therefore, in order to make a first contact with metallic powder handling and machine care, some maintenance operations were conducted on a commercially available SLM system.

In order to be able to safely work with metal powder, appropriate protective gear had to be assured, namely laser safety goggles (for use with the prototype chamber, since it uses fibre laser and its prototype enclosure does not guarantee eye safety), respirator masks with appropriate filters (EN 143:2000 P3 R), cotton lab coats and security footwear with ESD protection (Electrostatic Discharge protection).

The maintenance activities were based on preparing the referred system for processing another type of powder metal, which requires a complete clean-up of the powder processing modules. In order to reuse the powder from the previous operation, this should be moved into an appropriate metal container, by using a shovel or a brush. Since the fine particles may become airborne, the usage of masks is critical (given that this material is highly dangerous for the respiratory system). Powder leftovers should then be aspirated, using a suitable Dust Class M aspirator (although aspirated powder cannot be recovered later on from the filters). Finally, all mechanical components should be cleaned with ethanol, to remove surface particles. Complex parts (such as tubing and valves) can be cleaned using an ultrasonic bath.

Cleaning and maintenance operations may present danger to the machine operator. Accumulated exhaust products on the gas circulation filters may be highly flammable and potentially explosive when contacting with the room air, which implies that all filter boxes should be sealable and closed before removing from the machine for replacing. Especially reactive powders, such as magnesium are much more probable to create these situations. Furthermore, argon atmospheres may be potentially dangerous in closed spaces, which means that processing should occur in a well ventilated facility, with alarm systems to detect irregular atmospheric conditions. Additionally, any containers which may leave the machine with powder, should have a sealing solution, in order to prevent it to disperse into the surrounding environment. Opening these containers should only be permitted when the cleaning process starts and everyone has the correct protective gear fully equipped.

All recovered powder should then be sieved, in order to remove abnormal particle sizes. For this, ultrasonic sieving solutions should be used, with fine meshes, depending on the grain size that was processed.

b) Prototype Test Stand Experimental Work

The experimental test stand which was designed for SLM process validation, allows the execution of limited processing operations and was designed with the main objective of testing the process chamber concept, its capability to maintain a suitable process atmosphere and evaluate the influence of different optical variables (such as laser power, scan speed or scan vector spacing) and process variables (such as gas circulation pump flow, powder layer disturbance due to the modular chamber movement speed or distance to the surface).

An analysis of the produced test stand assembly allowed an evaluation of the necessary components and suppliers for integrating this equipment into the machine, especially regarding the gas circulation system. The necessary steps in order to achieve and maintain processing conditions were undertaken and the implemented circuit is planned for installation on the final machine. Additionally, the process concept was discussed and different suggestions were considered, in order to improve setup times and reduce installation complexity.

For conducting laser processing with the prototype system, a powder layer was manually placed over several small substrates, fixed by a clamping system to the machine table. In order to do this, the powder was distributed by hand over the substrate. Afterwards, the modular chamber levelled the layer by using a carbon brush placed on its side. Finally, the modular chamber processed the powder layer by using the laser scanning equipment previously described on this report.

This activity allowed the production of different samples (figure 97) with one processed layer, using stainless steel metallic powder:

Figure 96 - Produced SLM samples on the modular test chamber. One layer was processed on top of a small metal substrate.

8. Conclusion

Throughout this thesis, a description of the fundamental research topics was made, leading to the more specific process know-how concepts (Metal AM) and finally to a description of the project itself and the development workflow that was carried out. This involved an initial concept theory review, which was useful for guaranteeing a good understanding of the processes at hand. A direct approach was chosen, from concept to reality, pointing out the main topics and modules that compose the development of Additive Manufacturing industrial machinery. This way, the so-called project puzzle can be assembled and the different challenges can be mapped out.

After the review of the involved topics, the necessary modules for implementing both the LMD and SLM processes were mapped out and the corresponding suppliers were contacted for the selection of new components. Afterwards, a demonstration system project was planned and started, first with the concept development and selection and, later on, with its implementation. This new system combines these two technologies, serving as the validation platform for both. The project calendar allowed for the implementation of the LMD process, which included a new process table and its integration within the original machine platform. The SLM project was also engaged and is currently being developed by the end of this thesis calendar.

Although not being possible to finish the complete project within the time frame of this Master’s thesis, which was expected due to the complexity of such endeavour, the performed activities allowed to participate in it from a very early stage and support the growth of the machine, leaving a personal mark in it. Work will continue and the project will be underway by the end of the semester (the established plan is described in the next section).

The opportunity of working in such a promising and technologically interesting project is the ideal source of motivation for this progressive learning experience. Although a strong background of theoretical research was needed, which is natural with any new process development, the knowledge obtained from working within a professional environment provided a very practical notion of the subjects at hand. New contacts were established and new challenges were presented each day, which meant an open-minded approach and involved great effort to catch up with the more experienced professionals.

This endeavour provided a complete follow-up on the product development, from its early preliminary studies phase, up until production, giving a broad perspective over the necessary steps for bringing an idea to life. It was possible to learn and implement two different breakthrough technologies, namely LMD and SLM, both at the cutting edge of process engineering. The highly innovative processing technology made this experience even more interesting, being a truly differentiating factor. Furthermore, a great variety of areas and work fields were involved, from commercial procurement and supplier contact to the more technical mechanical design and process studies, as well as project managing activities.

This way, it was certainly a non-linear and realistic way of tackling these challenges, while creating value in a professional environment. It should not be discarded that this thesis was made possible due to the cooperation between FEUP and ADIRA, as well as many more contacts established through important partnerships. In conclusion, the main objective of taking part into a broad and enriching learning experience that creates value for both the student and the involved entities is considered accomplished.

9. Future Work

Due to the long and complex nature of this project (development of a Metal AM system), its completion within the 5 months' time frame for this thesis would not be likely. Therefore, as the machine development is still currently being carried out (until its unveiling by the end of the year), a plan for future work has been defined and the next steps are currently being undertaken.

As of the end of June 2016, according to the previously described plan, the experimental demonstration system (AM simulator) is on its detailed project phase, with production being started. The structures and components for the LMD process have been developed and are currently being produced, hence the remainder of the project will be focused on the SLM part, as well as common modules, such as the external coverage or the dual-head gantry system (adaptations to the original one). In parallel, electrical project, software and command implementation will also commence. This will involve the previously defined partners and suppliers.

LMD and SLM process development, testing and validation will take place as soon as the prototype is completed. This will involve close work with Fraunhofer ILT experts at this later stage. Machine completion is due for September 2016, allowing for final tuning and optimization until its unveiling at specialty fairs, by October.

During this final stage of this thesis, the SLM process implementation is underway. For this, a selection of the necessary components is being made and the correspondent suppliers are being contacted. Moreover, the parts which compose the modular chamber are being designed for production at ADIRA, allowing in-house development and modification of the already available prototype, therefore achieving its final version.

On the other hand, the powder storage, processing area (powder bed) and delivery modules are being developed in cooperation with the Portuguese institute INEGI and are currently at the concept development stage, due to finish by the end of June (as seen on figure 98). Afterwards, the necessary detailed production drawings will be made for starting part production and the necessary industrialization is assured by ADIRA. This work is being carried out with constant mutual feedback and close follow-up of the several taken steps, through regular meetings.

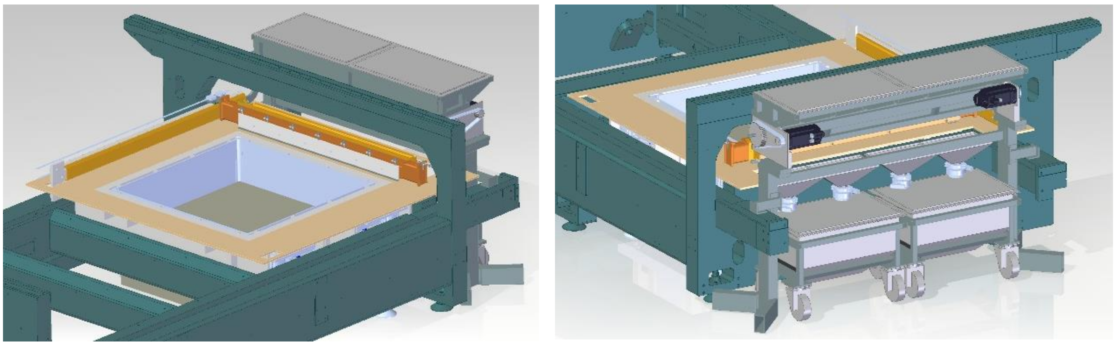

Figure 97 - Conceptual CAD design of the new SLM subsystem, currently under development (ADIRA/INEGI cooperation).

The principle for powder storage and supply is the one described on section 6.2c and the distribution concept is the one developed in the early project phases and explained on 7.2b. The powder bed structure is developed in a modular way with a 1000x1000 mm process area, allowing it to be assembled independently and fixed on the machine platform afterwards. It is also directly supported on the ground. Other features such as argon pressurized storage or rolling overflow containers (for easy removal from the machine for cleaning operations and outside powder recycling) are being planned.

Meanwhile, the machine platform itself and all the regular modules already implemented in the laser-cutting systems are being produced (figure 99). Currently, its main structure has been assembled and the remaining components are set for the next stages, starting off with the LMD side (developed first) and finishing off with the SLM process (with a prolonged development schedule). Mechanical project will continue after the end of this thesis period, in order to guarantee project completion by the end of September, for the unveiling.

Figure 98 - Assembly of the AM Simulator structure is currently underway (June 2016).

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Annex

A1. Laser Processing Head Modular Concept

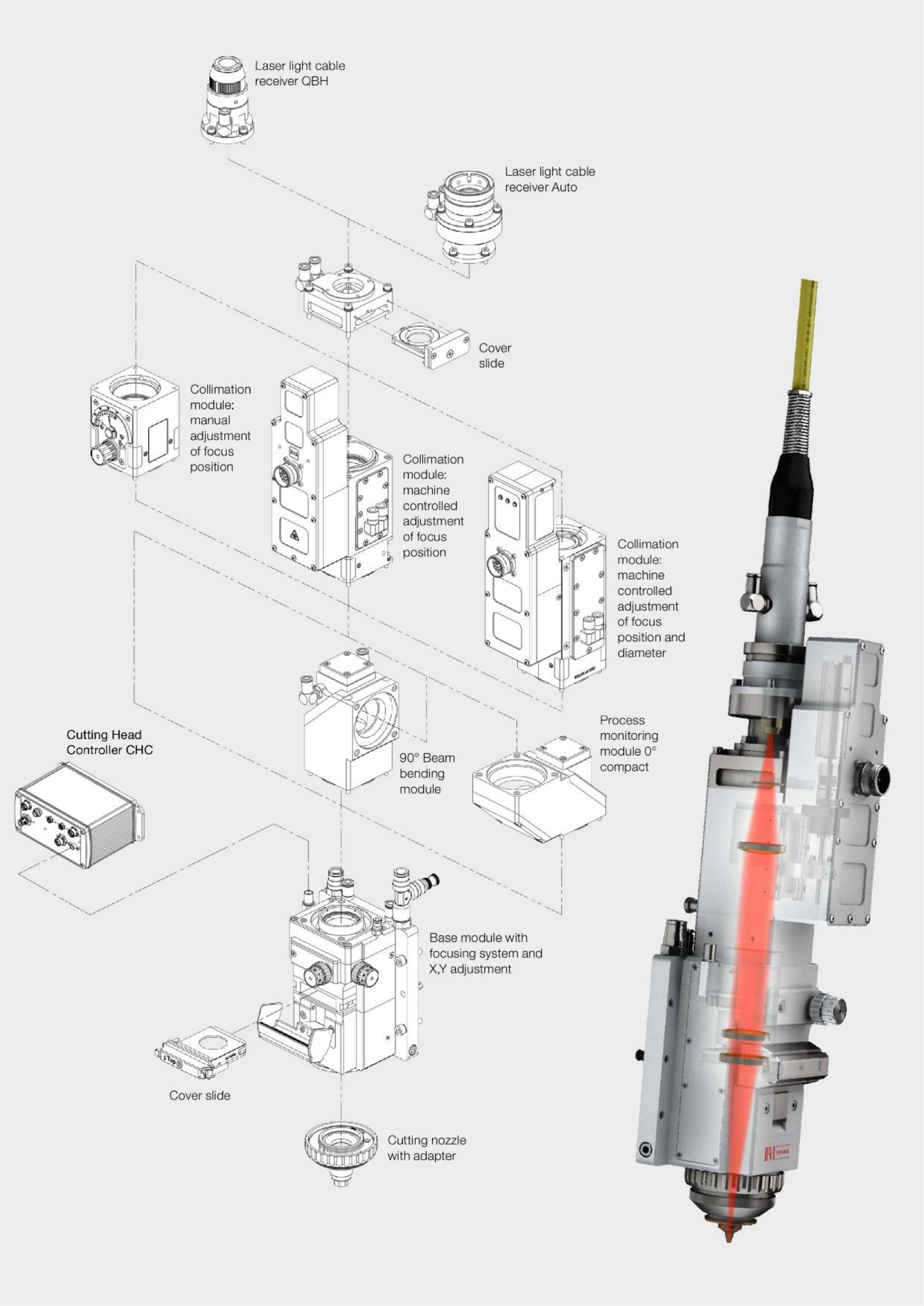


Figure 99 - Laser Processing Head modular assembly concept [57].

A2. LMD System Market Benchmarking

Insstek DMT® Systems

Insstek, a South Korean company specialized in the development of metal DED systems has released some of the largest dedicated LMD systems presently available. The company refers the technology as DMT, Direct Metal Tooling and focuses its application on repairing metallic parts and tooling by DED. DMT systems are compatible with 3-axis or more complex trajectory operations, as well as accepting different powder metal materials, from stainless and tool steels to titanium, nickel and cobalt based super alloys [6].

Their largest system, the MX-Grand is a custom-made machine with a 5 kW laser source, 6 movement axis, a fully working envelope of 2 x 1 x 1 metres (expandable to 4 x 1 x 1 metres using only 3 axis operations) and 3 powder-feeding systems (figure 101). This machine was developed for big metallic part repairs in mind, from a partnership with the South Korean Air Force for the repair and modification of large 800 mm turbine components [58, 59].

Other systems are available within the DMT systems range, such as the MX-1000 (with a 2 kW laser source and a work envelope of 1000 x 800 x 650 mm) or the smaller MX-450.

Figure 100 - Insstek MX-Grand (left) and MX-1000 (right) systems [58].

Optomec LENS® Systems

One of the current references in DED metal processing, Optomec has developed the LENS (Laser-engineered Net Shaping) process which use high-power for metal deposition, along with closed-loop process parameter control, to achieve geometrical and mechanical integrity for the final parts. Argon-based protective atmosphere is employed, by using a suitable hermetically sealed enclosure, achieving oxygen levels below 10 ppm, preventing part oxidation.

The largest LENS printer available is the LENS 850-R (figure 102), with a 5-axis work volume of 900 x 1500 x 900 mm, focused on repair, rework and modification of large industrial components, using a 1 or 2 kW IPG fibre laser. Other solutions are available, such as the smaller MR-7 or the entry-level LENS 450 (figure 102) [60].

Figure 101 - Optomec LENS systems: the larger 850-R (left) and the smaller entry-level LENS 450 (right) [60].

Hybrid Laser Systems

Major system manufacturers, such as Trumpf (Germany) or DMG Mori (Japan) have invested on developing hybrid laser systems, which implement LMD technology as part of the machine capabilities for laser processing. This way, a more versatile approach is possible, although increasing machine complexity to another level.

Trumpf's laser portfolio includes different systems for welding, cutting, marking or hardening, therefore metal deposition was a strategic approach that would fit in the existing strategy. AM-dedicated systems are available, as well as upgrade packages for the existing machines, giving them LMD capabilities [6].

The Trumpf TruLaser Cell 3000, 5-axis laser cutting, welding and metal deposition operations are possible, with a more compact 800 x 600 x 400 mm work volume and laser power of up to 8 kW. For larger processing operations, the TruLaser Cell Series 7000 (figure 103) offers a work volume of up to 4 x 1.5 x 2 m, with the possibility to use a dual-table configuration (for increased productivity) [61].

Another market reference is the DMG Mori Seiki Lasertec 65 3D (figure 103), a hybrid metal system for 5-axis operations, which includes both LMD and machining for one-step part production. With a 2 kW diode laser, high precision operations can be performed with very high deposition rates of up to 1 kg/h [6].

Figure 102 - Hybrid laser processing solutions: the DMG Mori Seiki Lasertec 65 3D (left) and the Trumpf TruLaser Cell 7000 (right).

More Systems

A more extended table with additional systems is available next (table 1).

Table 1 - Existing LMD systems benchmarking table.

Make	Model	Build Envelope (mm)	Build Rate	Layer Thickness	Material Supply	Laser Configuration	Inert Gas Atmosphere	Dimensions (mm)	Price
Insstek	MX-1000	1000x800x650 - 3 or 5 axis motion	N/A	150/250/450 µm	N/A	2 KW Ytterbium Fiber Laser	N/A	N/A	900,000$
Insstek	MX-Grand	4000x1000x1000 - 6 axis motion 2000x1000x1000 - 3 axis mode	N/A	100 to 1000 µm	3x metal powder hoppers	5 KW Ytterbium Fiber Laser	N/A	N/A	Custom
Optomec	LENS 850-R	950x1500x900 - 5 axis	0,5 kg/h	0,25 mm	2x14 kg feeders	1 to 4 KW IPG Fiber Laser	Argon, O2<10 ppm	3x3x3 m	995,000 $
Optomec	LENS 450	100x100x100 - 3 axis	80 g/h	0,25 mm	1 or 2 feeders (2 kg each)	400 W IPG Fiber Laser	Yes, Argon	1x1x1,5 m	299,000 $
Optomec	MR-7	300x300x300 - 3 axis	0,1 kg/h	0,25 mm	2L feeders - up to 4	500 W. 1 or 2 KW IPG Fiber Laser	Argon, O2<10 ppm	N/A	620,000 $
BeAM Machines	Mobile CLAD	400x250x200 - 3 or 5 axis	20 to 300 cm3/h; 0,8 to 1,2 mm deposit size	N/A	1 or 2 powder hoppers: 45 - 90 µm powder	Laser Fiber Multimode 500 W	Yes	1320x1210x2300	350,000 to 750,000 €
BeAM Machines	MAGIC 2.0	1200x700x700 (5 axis) 550x700x1400 (3 axis)	20 to 300 cm3/h; 0,8 to 4 mm deposit size	0,2 to 0,8 mm	2+ powder hoppers: 45 - 90 µm powder	IPG 2/3/4 KW, 300 mm focal	8 m3 Argon, O2<40 ppm; H2O<50 ppm; 7,5 bar	3600x2000x3100	900,00 to 1,3 million €
RPM Innovations	RPMI 557	Aprox. 1500x1500x2100 (5 axis)	N/A	N/A	2+ powder hoppers	3 or 4 KW IPG Fiber Lasers	Argon, O2<10 ppm	N/A	N/A
Sciaky	EBW 300	5791x1219x1219 (3 axis + Tilt)	3,2 to 9,1 kg/h; 0,05 mm accuracy	N/A	N/A	Electron Beam	Vácuo	7620x2743x3353	Aprox. 5 million $
Sciaky	EBW 110	1981x1194x1600 (3 axis + Tilt)	3,2 to 9,1 kg/h; 0,05 mm accuracy	N/A	N/A	Electron Beam	Vácuo	N/A	Aprox. 2,2 million $
Trumpf	TruLaser Cell 3000	800x600x400 (5 axis) ± 135° (B); 360° (C)	N/A	N/A	N/A	Up to 8 KW, Solid-state laser	N/A	1600x2840x2645	400.000 €
Trumpf	TruLaser Cell 7040	4000x2000x750 (5 axis) ± 135° (B); 360° (C)	N/A	N/A	N/A	Up to 15 KW CO2 Up to 6,6 KW Fiber	N/A	N/A	750.000 €
DMG MORI	LASERTEC 65	735x650x560 (5 axis) - hybrid system	1 kg/h	0,3 mm	1 or 2 powder feeders; 5L capacity	2 KW Fiber Laser, 200 mm focal length, 600 µm fiber diameter, 3 mm spot diameter	N/A	4180x3487x2884	500,000 $

A3. SLM System Market Benchmarking

Concept Laser LaserCUSING® Systems

One of the current references for the SLM market is Concept Laser (Germany), which produces and sells PBF systems since 2002. Their specific scanning routines which follow a pattern approach compose the LaserCusing system, which is aided by proprietary melt pool monitoring solutions, in order to prevent part distortion due to excessive stresses.

The company produces the largest PBF system commercially available, the Xline 2000R, with a work volume of 800 x 400 x 500 mm, although its core operation is around the more standard machines, such as the M2, with different single and dual laser configurations, for increased productivity (figure 104) [6].

Figure 103 -Concept Laser M2 (left) and Xline 2000R (right) laser systems [49].

SLM Solutions Systems

SLM Solutions GmbH (Germany) is one of the current major players in the PBF system industry, although only formed in 2010. With different laser systems available, for different work volume capabilities, its machines work with an open system architecture, allowing most metallic powders to be used. Additionally, tandem laser solutions (parallel processing of the powder bed for improved flexibility and speed) are an important feature, present on the more high-end SLM 280 HL and 500 HL systems. The last one includes up to four laser scanning heads with different power combinations (400 W or 1 kW lasers) for processing boundaries and internal sections of the produced parts separately (increasing build rate).

Other important technologies have been implemented by this company, such as a proprietary closed-loop powder system, which allows automatic powder recycling, making use of the excess material for the next build job, all within an inert atmosphere environment. The

PSX 500 sieving station may be combined with the 500 HL (figure 105) system to enable this feature.

Figure 104 - The flagship SLM 500 HL system from SLM Solutions [50].

Other Systems

Additional systems are currently available from different manufacturers, such as EOS (Germany), Arcam (Sweden) or Renishaw (UK). Further system specifications may be found on table 2.

Table 2 - Existing SLM systems benchmarking table.

Make	Model	Build Envelope (mm)	Build Rate	Layer Thickness	Material Supply	Laser Configuration	Focus Diameter	Scan Speed	Inert Gas Atmosphere	Dimensions (mm)	Price
Concept Laser	X line 2000R	800x400x500	Close to 120 cm3/h	30 - 150 µm	Proprietary Al, Ti, Ni; Sieving station, Powder silo	2x Fiber Laser (1 KW)	100 - 500 µm	7 m/s	Max. Temperature 200 °C; N2 atmosphere (17-34 L/min)	5235x3655x3304	1,575,000 €
Concept Laser	M2 Cusing	250x250x280	2 - 35 cm3/h	20 - 80 µm	N/A	2x 200/400 W	50 - 500 µm	7 m/s, 4.5 m/s variable focus mode	N2 generation (<1 m3/h)	2706x1818x1985	449.000 €
Sisma	mysint	Ø100x100	N/A	20 - 30 µm	Aço inox, CoCr, bronze, precious metals	Fiber Laser - 200 W, F-Theta Lens	55 µm	N/A	0,3% O2 concentration; N2 or Argon inert gas (<0,3 L/min)	N/A	165.000 €
Renishaw	RenAM 500M	250x250x350	N/A	N/A	Ti, Inconel, Al	500W Ytterbium fiber laser	N/A	N/A	N/A	N/A	N/A
Renishaw	AM250+	250x250x350	N/A	20 µm	Inconel, Stainless Steel, Cobalt Chrome, Aluminum and Titanium	200W (optional 400W)	N/A	N/A	N/A	N/A	360,000 £
EOS	M 400	400x400x400	N/A	90 µm	N/A	1 KW Yb-Fiber Laser; F-Theta Lens	90 µm	7 m/s	N2 generation	4181x1613x2355	1,250,000 €
SLM Solutions	SLM 500HL	500x280x325	105 cm3/h	20 - 75 µm	Inox, Ti, CoCr, Ni	2x/4x IPG Fiber Laser; 400/700 W	80 - 115 µm	10 m/s	Argon, 5-7L/min	5200x2800x2700	700.000 €
Arcam	Q20	Ø350×380	N/A	180 µm	N/A	3KW	180 µm	N/A	Vacuum atmosphere, He partial pressure - 4L/h	2300x1300x2600	800.000 €

A4. Current ADIRA Laser-Cutting Range

Since laser technology is especially interesting for the proposed Metal AM technologies that are planned for implementation, the current range of ADIRA machines in this domain received special attention in this report. Currently, ADIRA has available two different systems, both with gas (CO_2) and fibre laser options.

a) BL / LE

The entry-level ADIRA systems are the BL 1530 and the LE 1530. These systems use the same platform, with a work area that can process sheet metal up to 1500 x 3000 mm and a vertical travel of 200 mm. The main difference between both products is related to the used laser source:

- The BL system uses a solid-state fibre laser, allowing for reduced electric and gas consumption (only cut assistance gas necessary). Additionally, due to the used laser source, it is more suitable for processing reflective materials, with reduced maintenance costs. The BL designation stands for Blue Laser, referring to the high efficiency laser technology which is implemented;
- The LE system is based on the CO_2 gas laser solution, presenting high versatility, especially for increased metal sheet thickness. It is the most price-focused solution, since the laser technology implemented is less expensive.

These machines are also prepared for integration within a production chain with complementary solutions for automatic sheet metal feed and removal. The pinion-rack movement employed to the gantry system guarantees high speed and acceleration, along with optimum precision for laser cutting. [52]

During this project, the AM system development will be carried out on this platform, more specifically the fibre laser system (hence the frequent references to the BL 1530 machine). The specifications for both systems are detailed in the following table:

Table 3 - LE/BL system specifications.

Model		**LE 1530 / BL 1530**
Maximum plate dimension	mm	1500 x 3000
Travel X	mm	1525
Travel Y	mm	3025
Travel Z	mm	200
Positioning speed in X	m/min	80
Positioning speed in Y	m/min	80
Simultaneous positioning speed in X,Y	m/min	110
Position speed in Z	m/min	80
Maximum acceleration	G	Better than 1G
Positioning accuracy	mm	Better than ±0,05
Standard dimensions (L x W x H)	mm	9000 x 5000 x 2200
Approximate weight	Kg	8000

Figure 105 - The BL/LE platform with automatic table removal system [62].

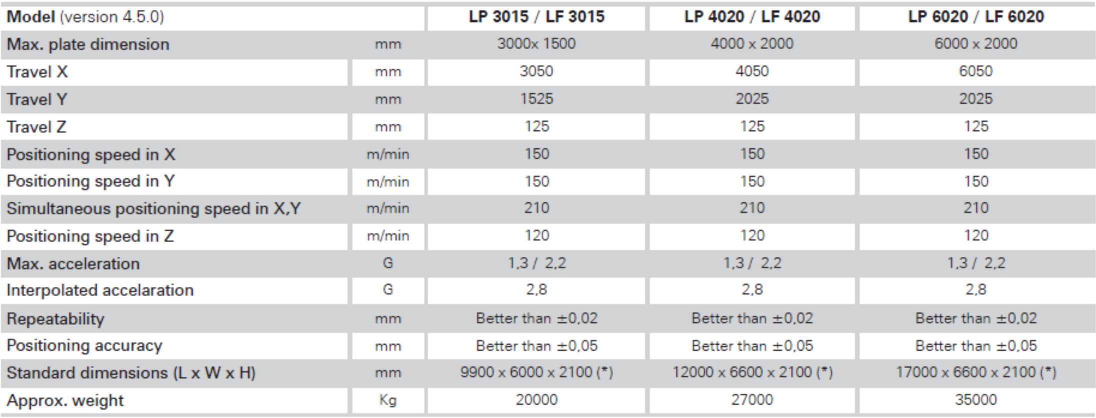
b) LF / LP

With a more premium approach in mind, ADIRA's LP and LF laser systems present additional configurations and greater flexibility, in order to suit the needs of different customers. As with the entry-level range, both systems share the same platform, although with different laser sources (the LP uses a CO_2 SLAB-type Laser and the LF implements a fibre laser).

The used components are all focused on the premium nature of this product, with promised reliability and reduced maintenance necessity. Movement is guaranteed by high speed linear motors. Several solutions are also available for production line integration, as special project, per request of the customer. [63]

Three standard configurations are present (with the possibility of custom projects, after consulting the manufacturer): the LP/LF 3015 (with 3000 x 1500 mm work area), LP/LF 4020 (4000 x 2000 mm) and the LP/LF 6020 (large 6000 x 2000 mm area). The specifications are presented next:

Table 4 - LP/LF system specifications.



Model (version 4.5.0)		**LP 3015** / **LF 3015**	**LP 4020** / **LF 4020**	**LP 6020** / **LF 6020**
Max. plate dimension	mm	3000x 1500	4000 x 2000	6000 x 2000
Travel X	mm	3050	4050	6050
Travel Y	mm	1525	2025	2025
Travel Z	mm	125	125	125
Positioning speed in X	m/min	150	150	150
Positioning speed in Y	m/min	150	150	150
Simultaneous positioning speed in X,Y	m/min	210	210	210
Positioning speed in Z	m/min	120	120	120
Max. acceleration	G	1,3 / 2,2	1,3 / 2,2	1,3 / 2,2
Interpolated accelaration	G	2,8	2,8	2,8
Repeatability	mm	Better than ±0,02	Better than ±0,02	Better than ±0,02
Positioning accuracy	mm	Better than ±0,05	Better than ±0,05	Better than ±0,05
Standard dimensions (L x W x H)	mm	9900 x 6000 x 2100 (*)	12000 x 6600 x 2100 (*)	17000 x 6600 x 2100 (*)
Approx. weight	Kg	20000	27000	35000

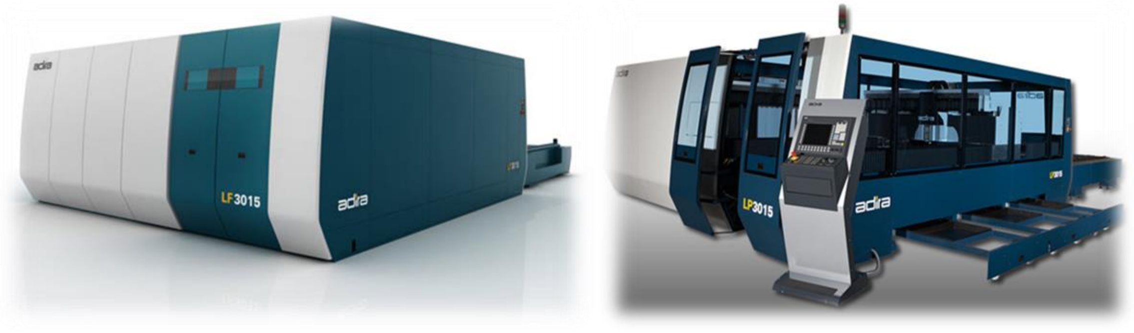


Figure 106 - The LP/LF high-end platform [63].

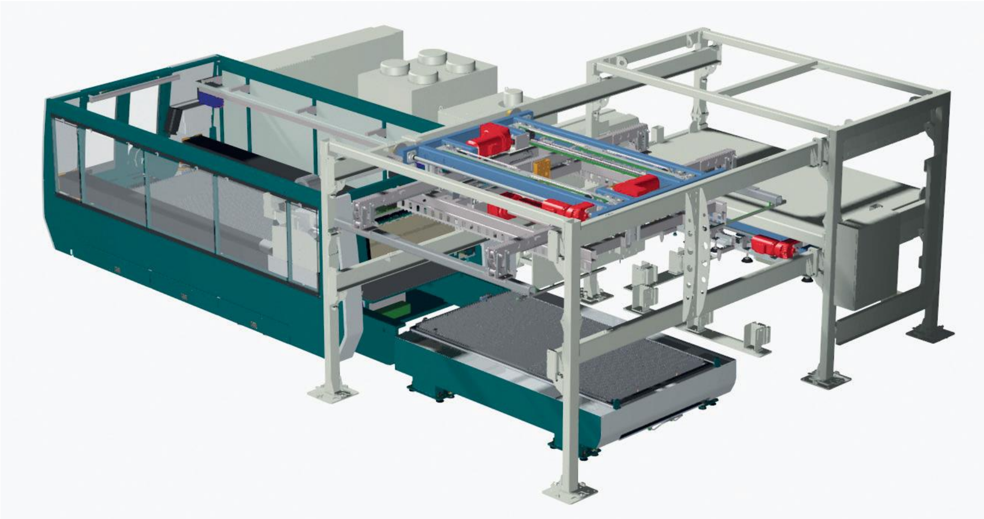


Figure 107 - Integration of the LP/LF platform in an industrial environment by making use of the automatic sheet metal handling systems [63].

Figure 108 - The largest LP6020 platform [63].

A5. Hybrid Table Weldment Details

As the weldment drawings were produced in A2 sized sheets, some separate details considered interesting are shown next, cut directly from the original drawing.

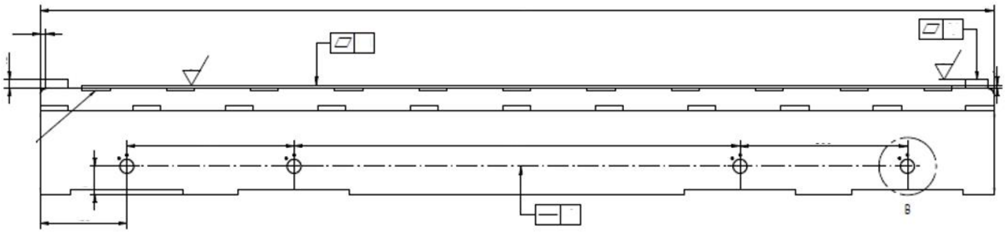


Figure 109 - Side view from the weldment 2D drawing.

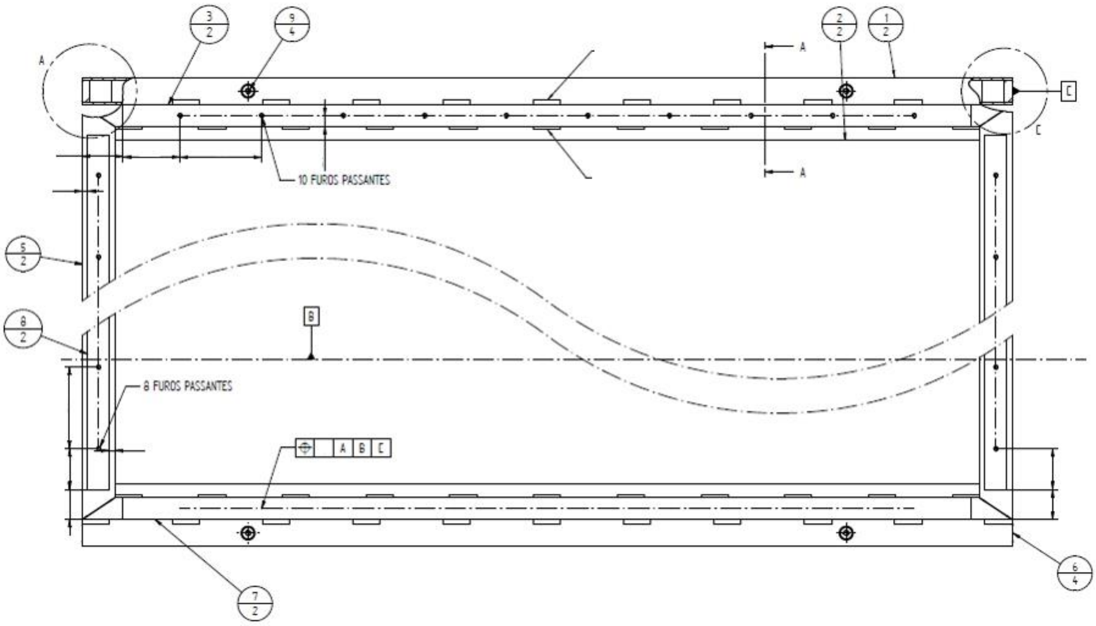


Figure 110 - Top view from the weldment 2D drawing.

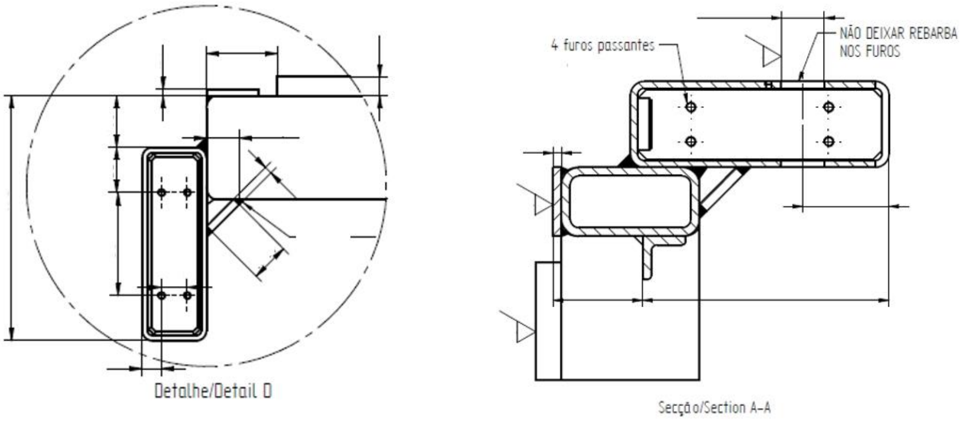


Figure 111 - Detail View D (left) and section view A (right).

A6. Slat Module Details

The following overview of the slat module was retrieved from a 2D draft of the CAD developed models (both assembled and exploded views):

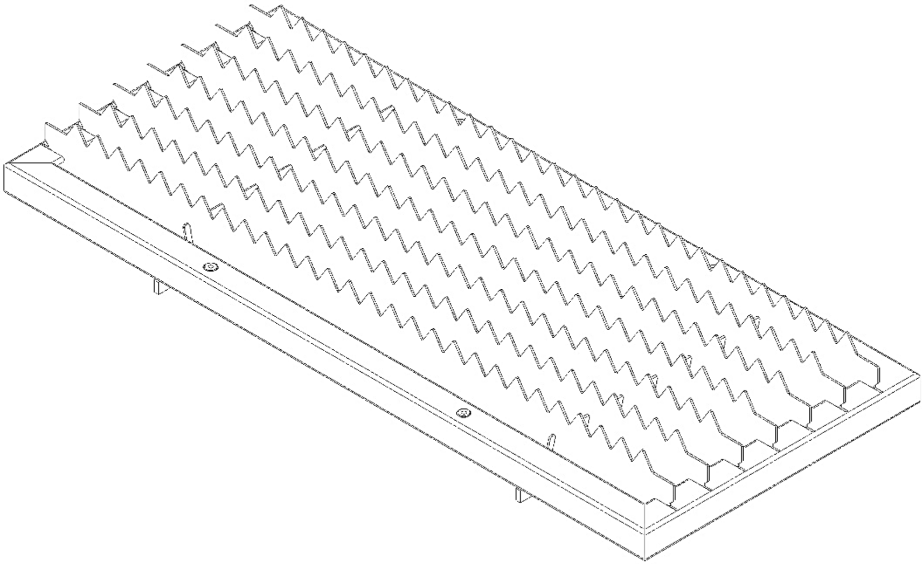


Figure 112 - Assembled Slat Module.

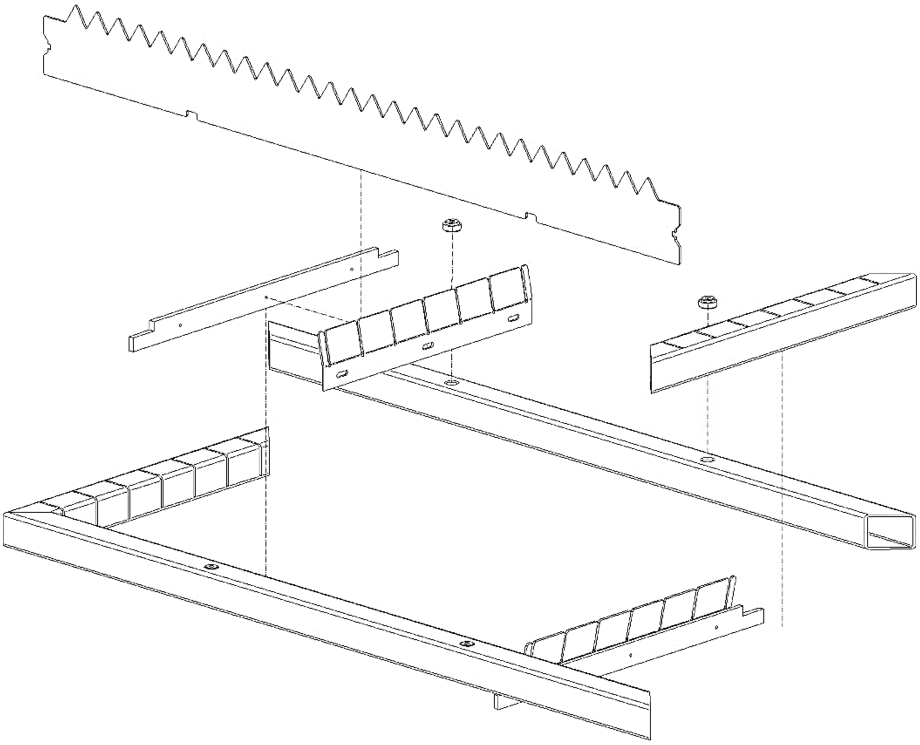


Figure 113 - Exploded view scheme from the slat module, showing the main components and their relationship.

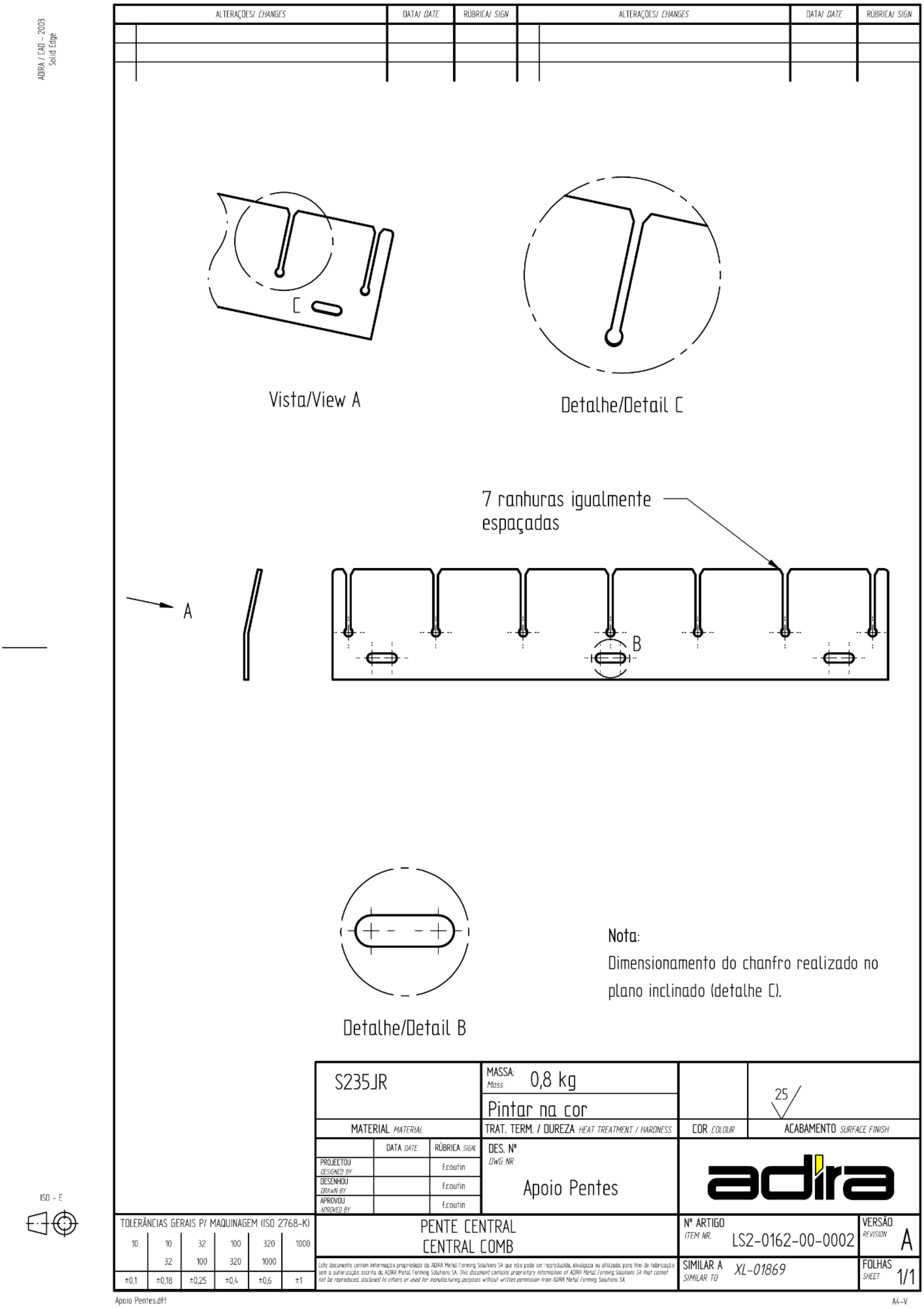


Figure 114 – Comb support production 2D drawing (in Portuguese; some details may be company-specific).

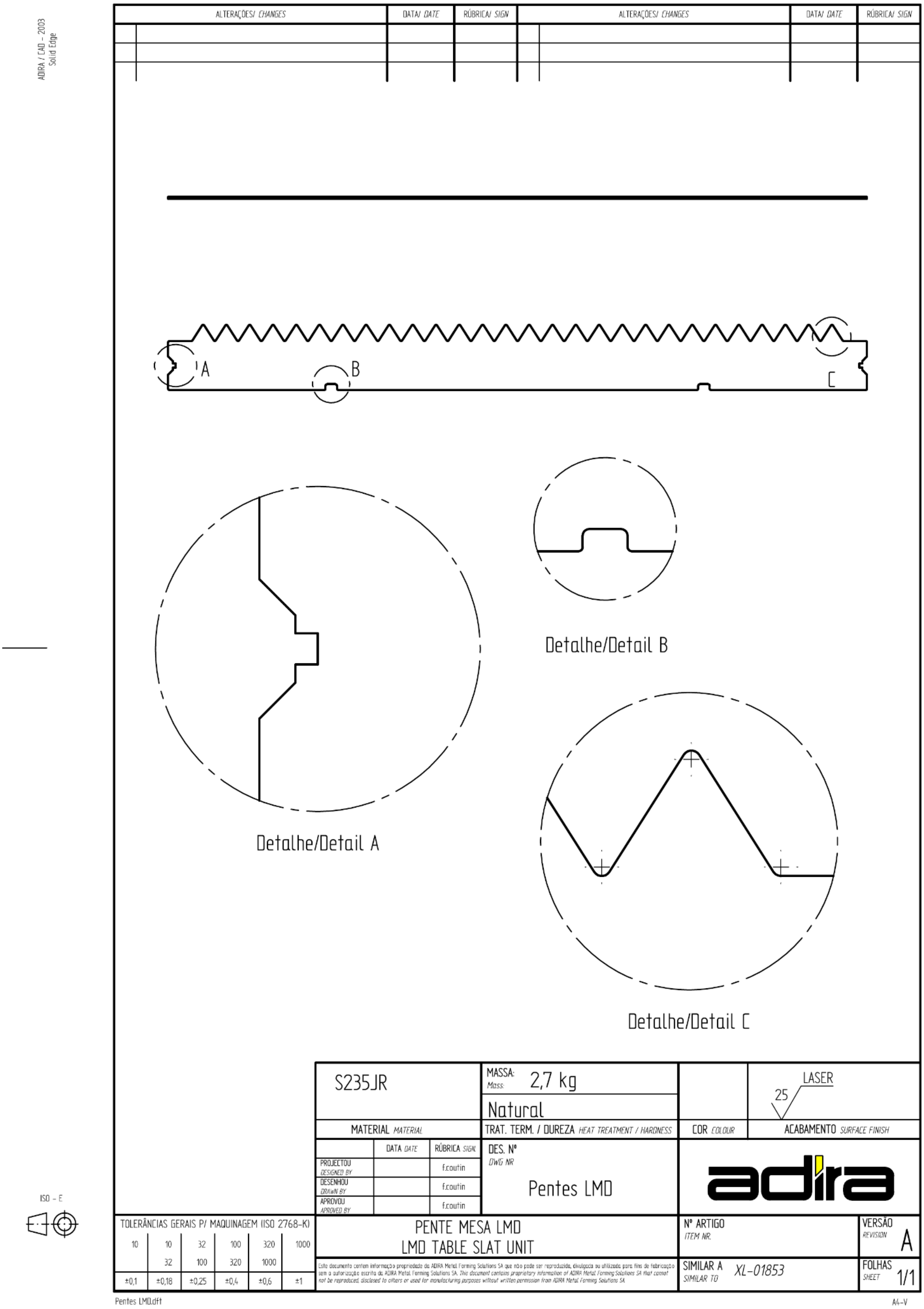


Figure 115 – Comb support production 2D drawing (in Portuguese; some details may be company-specific).

A7. LMD Crossbar 2D Drawing

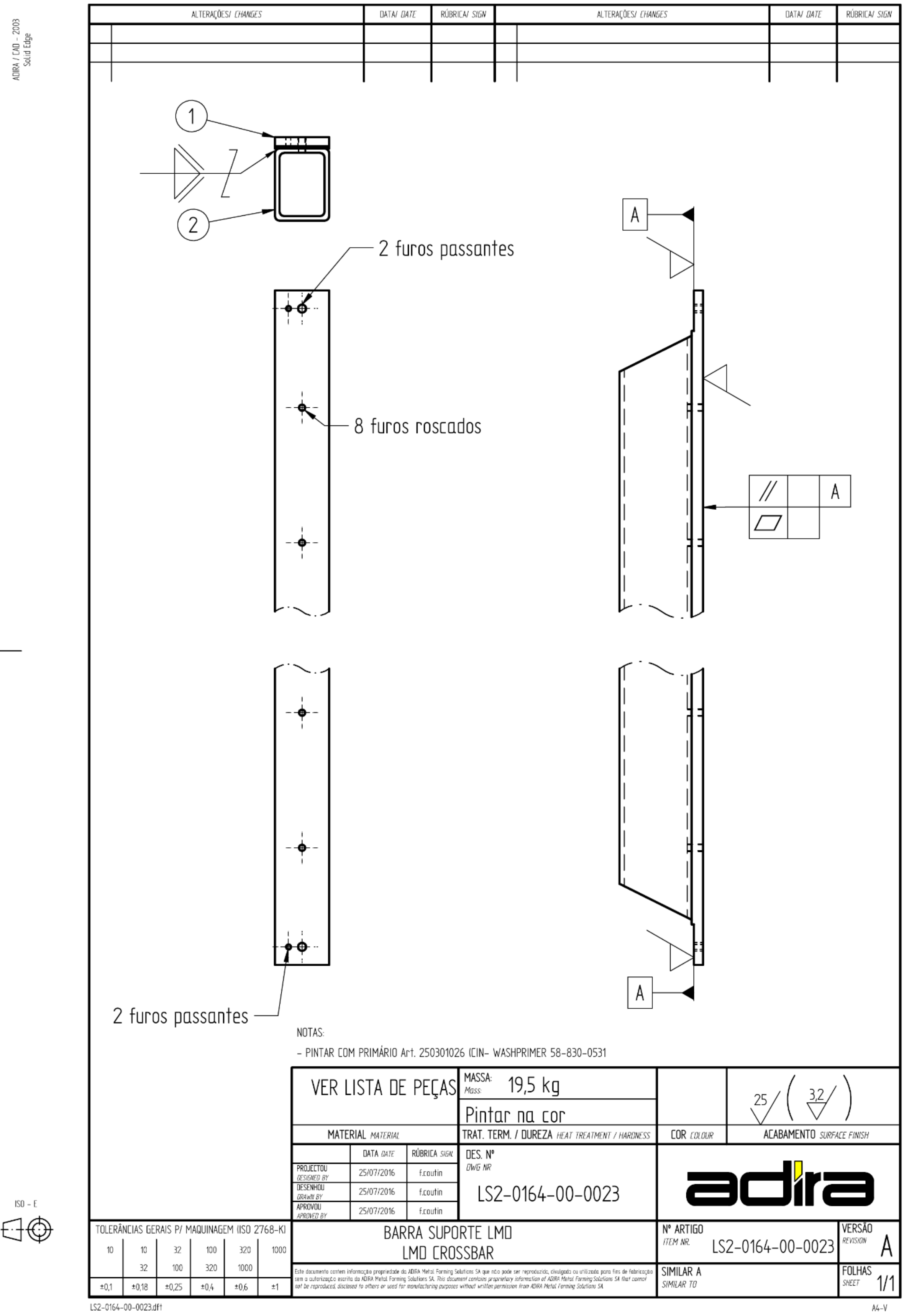


Figure 116 - LMD crossbar production 2D drawing (in Portuguese; some details may be company-specific).

A8. Hybrid Table Assembly Details

Some details from the assembly drawings are shown next. Notes from the production drawings are in Portuguese, as required by company policy.

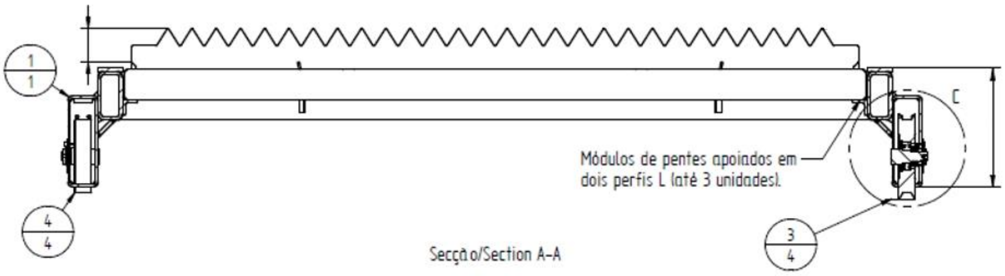
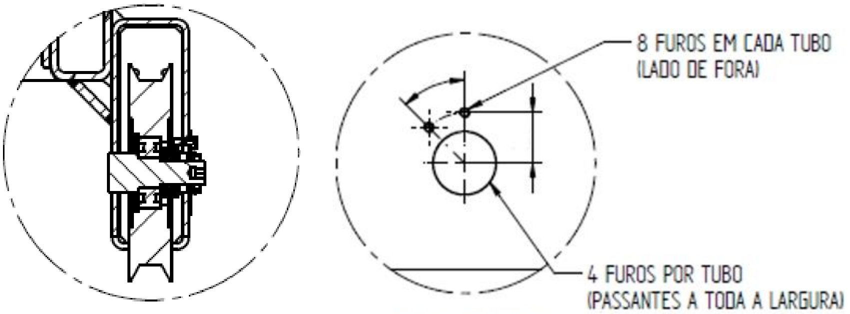


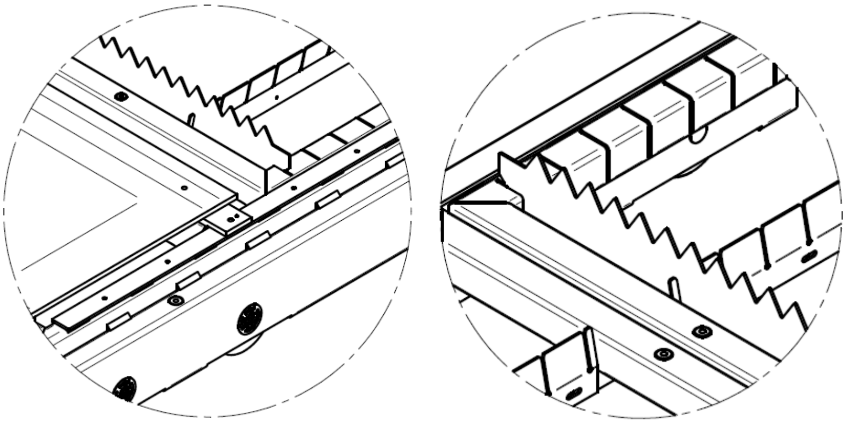
Figure 117 - Cutting view from of the table assembly.



Detalhe/Detail C

Detalhe/Detail B

Figure 118 - Detail view of the wheel assembly and hole placement.



Detalhe/Detail F

Detalhe/Detail E

Figure 119 - Detail F (LMD crossbar and work area assembly); Detail E (slat assembly).

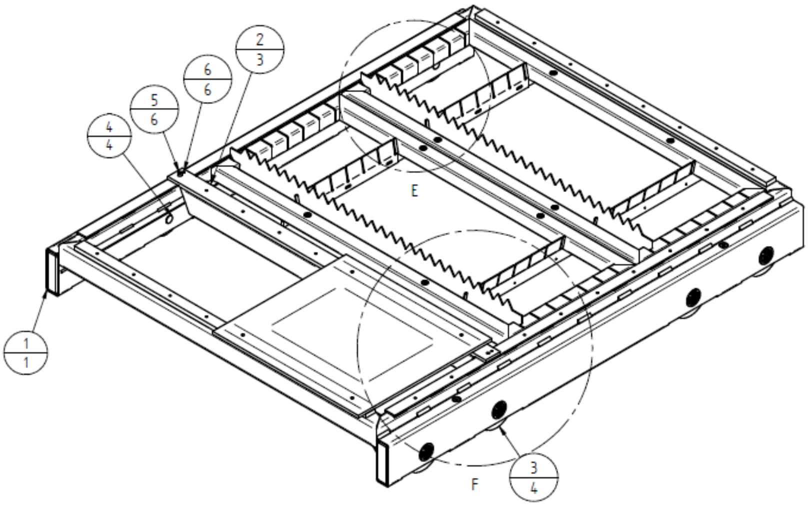


Figure 120 - Complete hybrid table assembly.

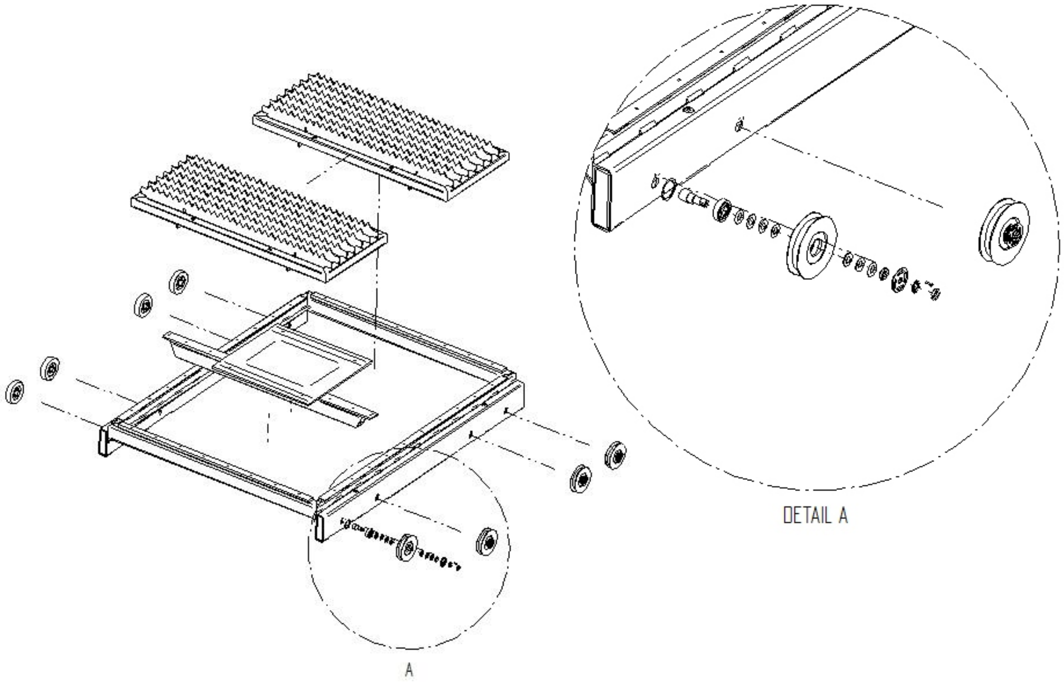


Figure 121 - Exploded view of the complete table assembly and detail of the eccentric wheel assembly.

A9. Left Support 2D Drawing

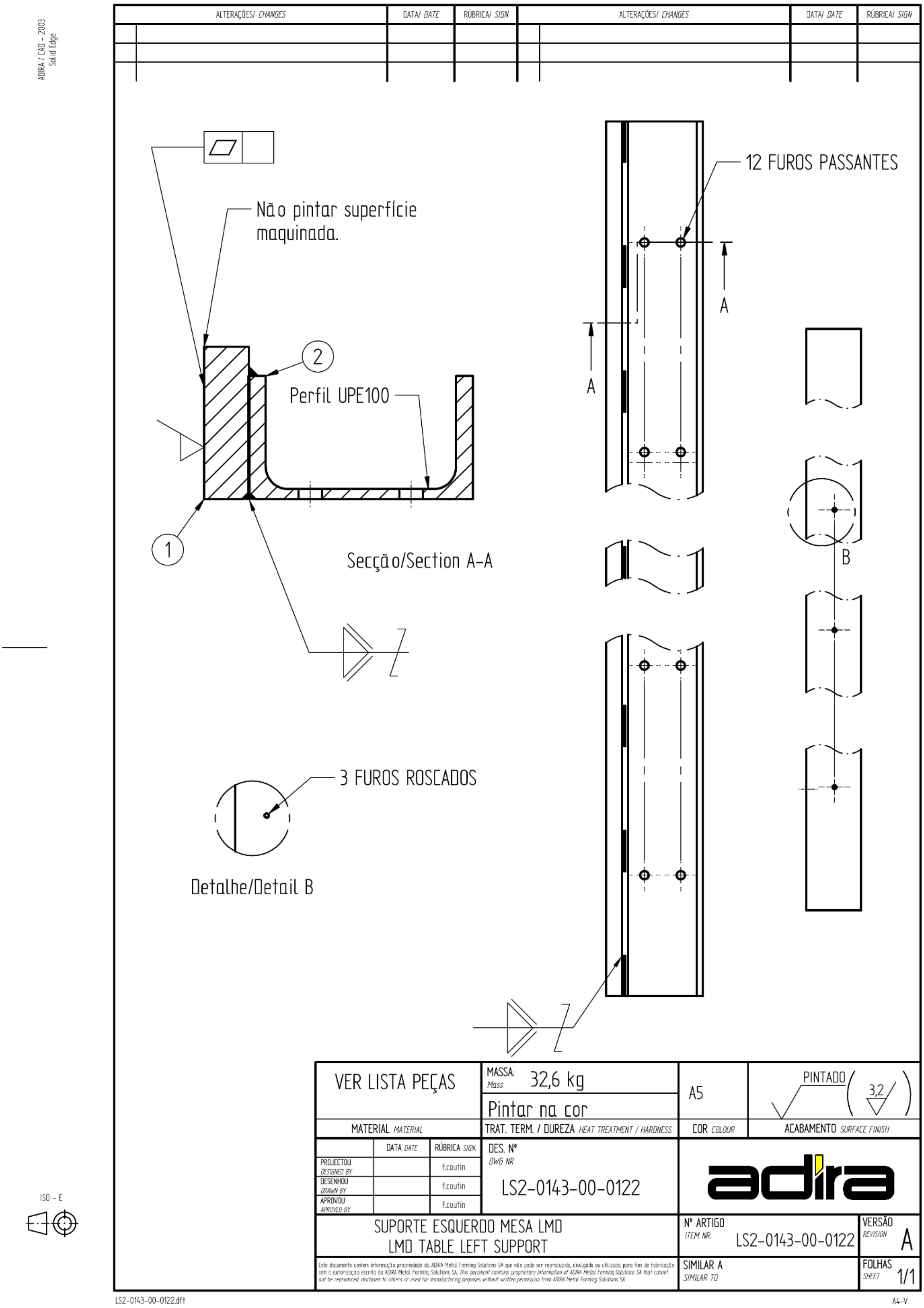


Figure 122 - LMD table left support production 2D drawing (in Portuguese; some details may be company-specific).

A10. Right Support 2D Drawing

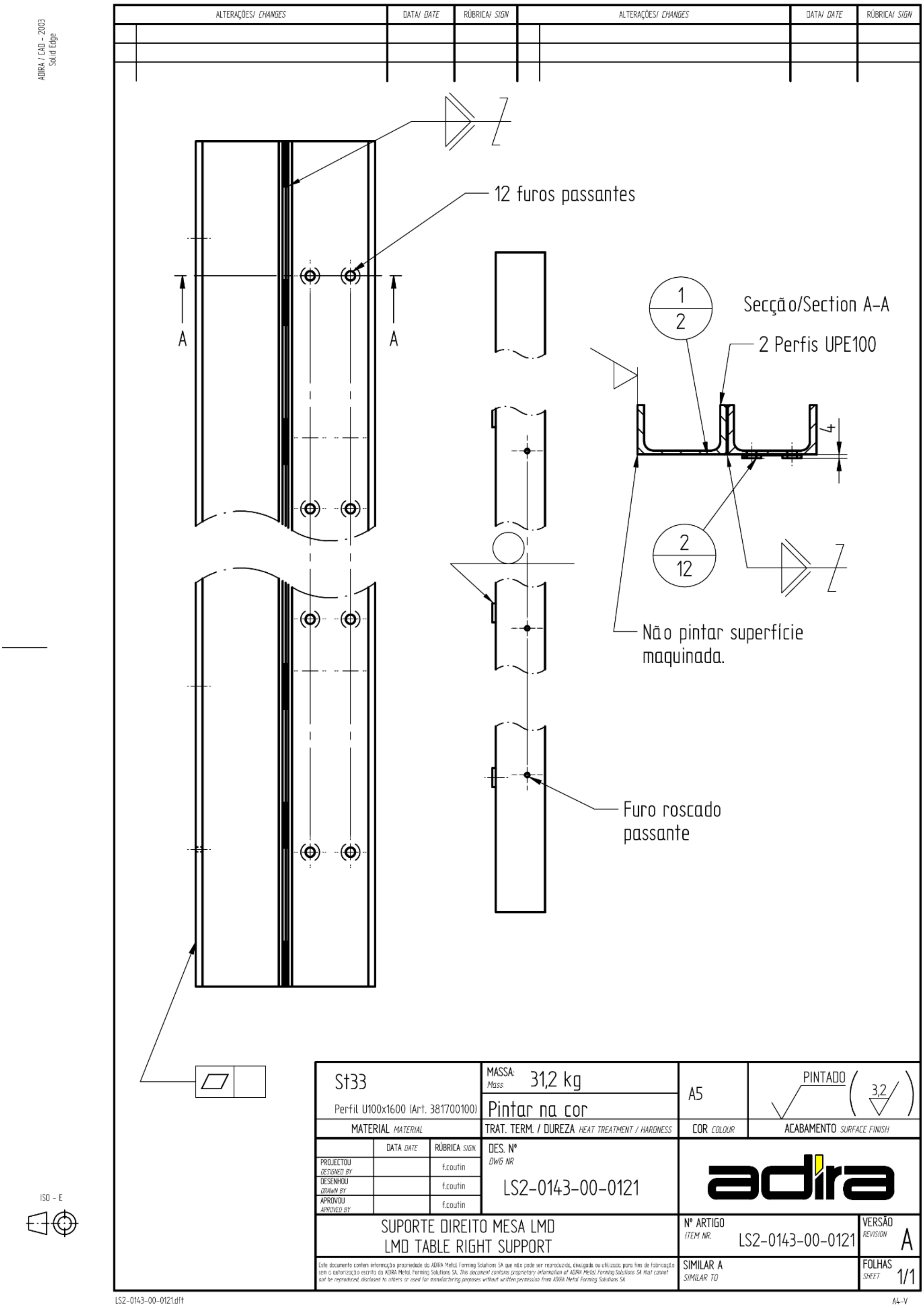


Figure 123 - LMD table right support production 2D drawing (in Portuguese; some details may be company-specific).

A11. LMD Table Installation Details

Some details from the assembly drawings are shown next. Notes from the production drawings are in Portuguese, as required by company policy.

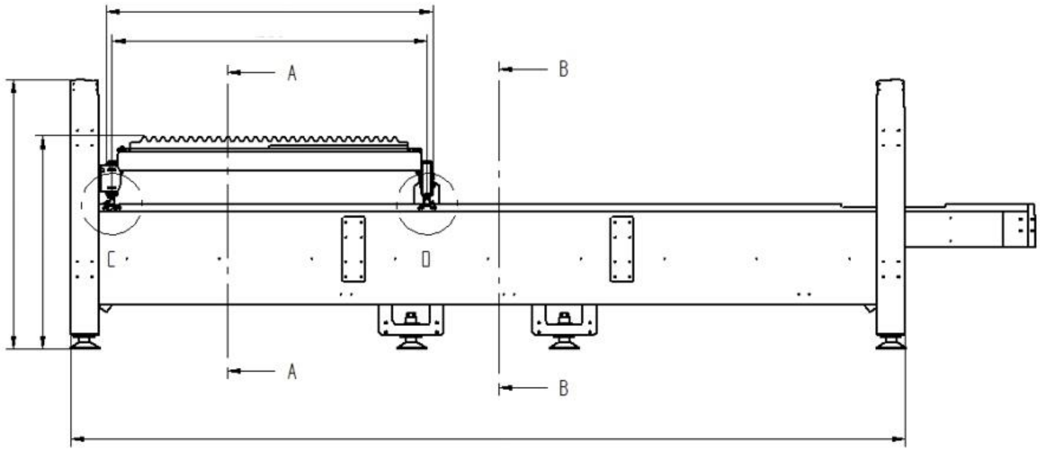


Figure 124 - Table assembly on the machine platform (side view).

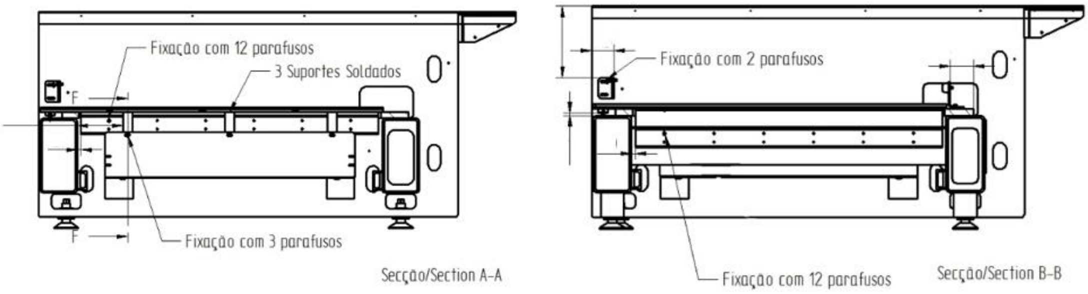


Figure 125 - Cut views of the machine platform, with the installation of both supports.

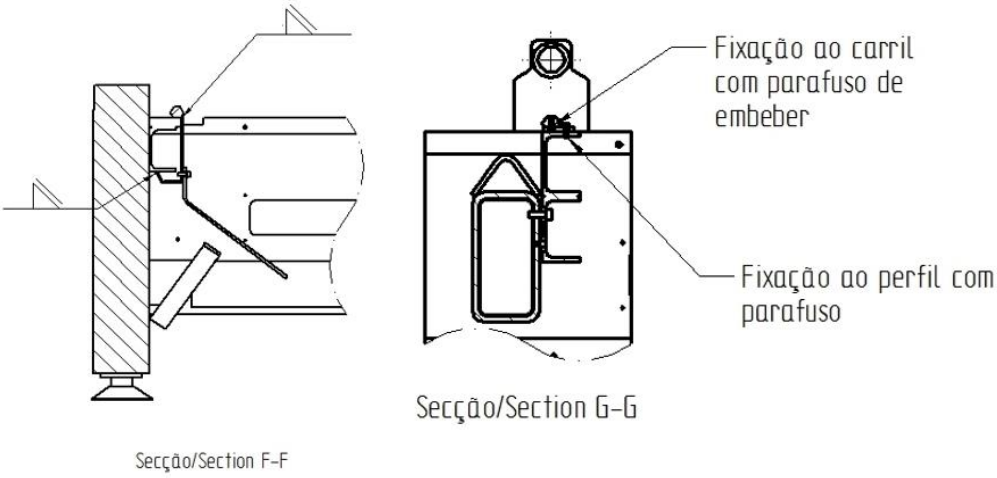


Figure 126 - Left support cut view (left) and right support rail installation (right).

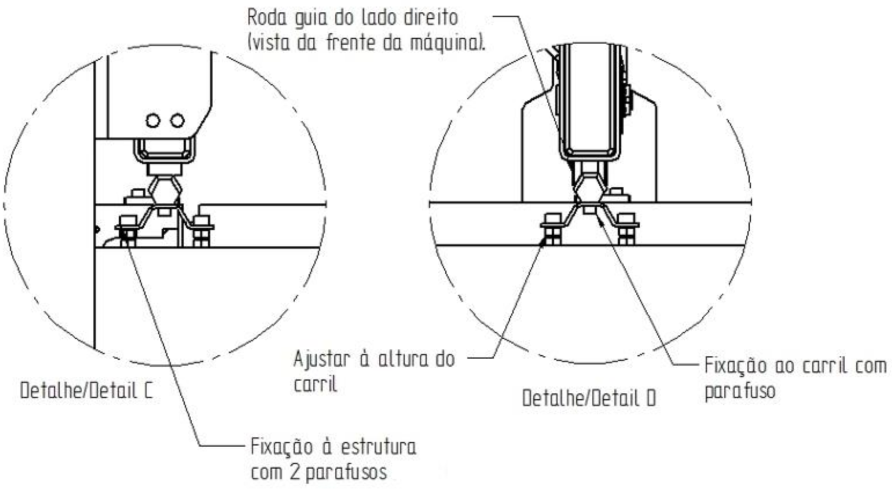


Figure 127 – Left and right assembled rail levelling systems.

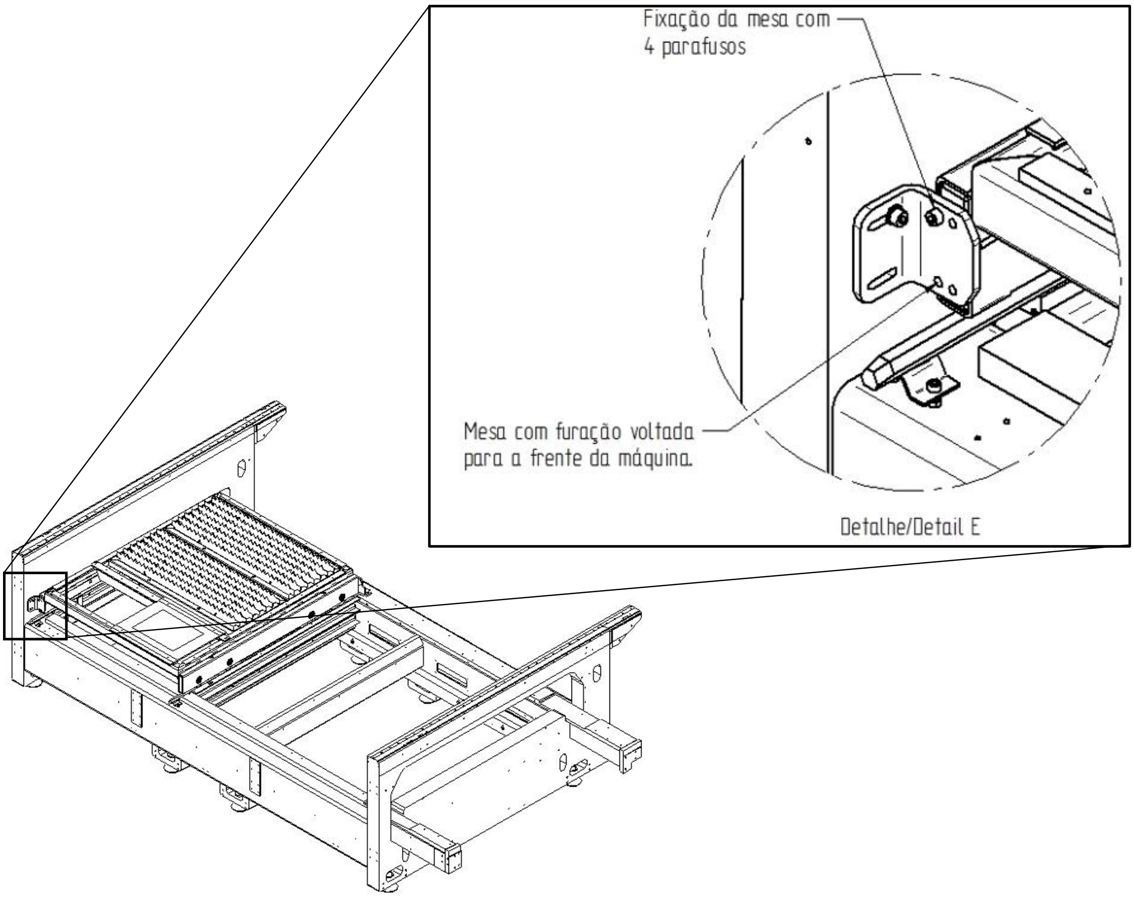


Figure 128 - Table locking system.