Cost Model for Additive Manufacturing of Metal in Aeronautics

Samuel Carreira Remédios

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Supervisor: Prof. Inês Esteves Ribeiro

Examination Committee

Chairperson: Prof. Filipe Szolnoky Ramos Pinto Cunha
Supervisor: Prof. Inês Esteves Ribeiro
Member of the Committee: Prof. Paulo Miguel Nogueira Peça

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All the content in the following pages is of its own authorship, resulting from the his study, investigation and his work.

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Abstract

Nowadays, with the parts manufacturing methods evolution, several industries are studying the changes possible of their manufacturing processes. Additive manufacturing emerges as a good alternative, given its several advantages, such as flexibility and geometric freedom or low costs at reduced production volumes when compared to traditional methods. Additive manufacturing in metals shows enormous potential for the aviation industry, and when compared with conventional methods it has shown several breakthroughs, among many the possibility of reduction of the aircraft weight, which is a constant challenge for engineers. Among all the convencional manufacturing processes of metal parts, forging presents itself as the method most used over time. Forging is a well-known method that offers a practical solution for the aerospace industry. However, with the increasing complexity of parts, the need for weight and stock reduction, additive manufacturing appears as the hypothesis to consider. The objective of this dissertation is to develop an economic and technological analysis of two most used Additive Manufacturing (AM) processes in metal parts, Direct Energy Deposition (DED) and Powder Bed Fusion (PBF) throughout the life cycle of a part, creating a model where it is possible to edit several production steps for a part, thus making this model unique allowing a deeper study of this theme. An analysis of environmental impact is also performed for each used technology, namely the quantification of possible environmental impacts associated with each process and each production step of it, hence resulting in a life cycle assement of the metal parts being produced.

Keywords

Additive Manufacturing, Aerospace, Metal Parts, Forging, Life Cycle Assessment, Environmental Impact

Resumo

Hoje em dia, com a evolução dos métodos de fabrico de peças, várias indústrias estudam a possibilidade de uma eventual mudança dos seus processos de manufactura. O fabrico aditivo surge como uma boa possibilidade, possuindo inúmeras vantagens, como a flexibilidade e liberdade geométrica ou os baixos custos associados a reduzidos volumes de produção quando comparados com os métodos tradicionais. A manufactura aditiva em metais tem mostrado um enorme potencial na indústria da aviação, e quando comparada com os métodos convencionais tem mostrado várias vantagens, entre muitas a possibilidade de redução de peso de uma aeronave, que é um dos constantes desafios da engenharia. Dos vários métodos convencionais, aquele com maior destaque é o forjamento, sendo o método convencional mais utilizado. O forjamento é um método bastante conhecido que oferece uma solução viável para a indústria aeroespacial. No entanto, com a complexidade das peças a aumentar, a necessidade de redução de peso das peças e a redução de estoques, o fabrico aditivo surge como uma hipótese a considerar. O objectivo desta dissertação é desenvolver uma análise económica e tecnológica para os dois processos mais usados no fabrico aditivo de peças metálicas, a Fusão em Cama de Pó e a Reposição Directa de Energia ao longo do ciclo de produção de uma peça, criando um modelo onde é possível editar várias etapas de produção. É, ainda, realizado um estudo de impacto ambiental das várias tecnologias e dos seus pós processamentos, resultando numa avaliação do ciclo de vida das peças de metal.

Palavras Chave

Manufactura Aditiva, Aeroespacial, Peças Metálicas, Forjamento, Ciclo de Vida, Impacto Ambiental

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Abbreviations

AM Additive Manufacturing

AMF Additive manufacturing File

APV Annual Production Volume

BJ Binder Jet

CAD Computer Aided Design

CMM Coordinate Measuring Machine

CNC Computer Numerical Control

DED Direct Energy Deposition

DMLS Direct Metal Laser Sintering

EBAM Electron-beam Additive Manufacturing

EBM Electron Beam Melting

EDM Electrical Discharge Machining

EOS Electro Optical Systems

FDM Fused Deposition Modeling

HIP Hot Isostatic Pressing

IM Injection Moulding

LCA Life Cycle Assessment

LCC Life Cycle Cost

LCI Life Cycle Inventory Analysis

LCIA Life Cycle Impact Assessment

LES Laser Engineered Net Shaping

LMD Laser Metal Deposition

LOM Laminated Object Manufacturing

LS Laser Sintering

LTA Line Time Available

MAM Metal additive manufacturing

MIT Massachusetts Institute of Technology

MJ Material Jetting

MM MultiAxis Mills

NC Numerical Control

PBCM Process-Based Cost Modeling

PBF Powder Bed Fusion

SGC Solid Ground Curing

SHS Selective Heat Sintering

SLCA Social Life Cycle Assessment

SLM Selective Laser Melting

SLS Selective Laser Synthesis

STI Stereolithography Instructions

STL Stereolithography

USA United States of America

UV Ultraviolet

List of Symbols

MP_DED_DP	Main Machine Price of DED Data Preparation
F_DED_DP	Footprint of DED Data Preparation
T_DED_DP	Time cycle of DED Data Preparation
$LaborT\_DED\_DP$	Labor Time of DED Data Preparation
$t_{holding}$	Setup Holding Time
t_{lc}	Laser Calibration
t_{pp}	Powder Preparation
t_{gp}	Inert Gas Preparation
$deposit_{rate}$	Deposition Rate
$mass_{AM}$	Mass of the AM Part
$mass_{forging}$	Mass of the Forged Part
BS_i	Batch Size of Process i
EU_elect_i	Electric Energy Used in Process i
EU_{gas_i}	Gas Used in Process i
MC_i	Maintenance Cost of Process i
AP_i	Auxiliar Equipment Price of Process i
F_i	Footprint of Process i
T_SETUP_i	Setup Time of Process i
T_DP_i	Time of Data Preparation of Process i
s_i	Scrap Rate of Process i
r_{DED}	Reject Rate of Process i
UD_{DED}	Unplanned Downtime of Process i
$LaborT_{DED}$	Labor Time of processs i
C_{DM}	Die Manufacturing Cost
N_{DIE}	Number of Parts that a Die Can Build
F	Escalation of complexity
C_{Die}	Cost of Die
$T\_loadunload_i$	Time of Load and Unload Machine i
T_cycle_i	Cycle Time of process i
$RM_{temp_{forging}}$	Critical Raw Material Temperature
DPY	Working Days/Year
NS	No Shifts
UB	Unpaid Breaks
PB	Paid Breaks
UD	Unplanned Downtime
sh	Salary Per Hour
p_e	Price of Electricity
p_b	Price of Building
p_g	Price of Gas
p_s	Price of Scrap
p_{RM}	Price of Raw Material
r	Interest Rate
$volume$	Part Volume
Max_height_part	Maximum Part Height
Max_width_part	Maximum Part Width
Max_lenght_part	Maximum Part Length
$thickness$	Minimum Thickness of Part

APV	Number of Good Per Year
RM	Raw Material
$forging\_1$	Hot or Cold Forging Selection
$forging\_2$	Forging Machines Selection
HT	Heat Treatments Selection
$forging\_FT$	Forging Finishing Treatments
AM_FT	AM Finishing Treatments
LTA_i	Line Time Available per Sep i
$effPV_i$	Effective Volume Production per Sep i
$reqLTi$	Required Line Time per Sep i
LR_i	Lines Required per Sep i
$Total\_costs$	Total Costs
RM_used	Raw Material Used
$mass\_req_i$	Mass Requerired per Step i
U_mass_i	Mass Usage left in the Stage i
$Nr\_bad\_parts_i$	Number of Bad Parts per Stage i
$Total\_mass_i$	Total Mass Left in the stage i
$MaterialCost_i$	Anual Material Costs in each Step
$MaterialSold_i$	Sold Scrapt per Sep i
APT_i	Annual Paid Time per Sep i
ALC_i	Annual Labor Cost per Sep i
AEU_elect_i	Annual Energy Usage per Sep i
AEC_i	Annual Energy Cost per Sep i
GAU_i	Annual Gas Usage per Sep i
AGC_i	Annual Gas Cost per Sep i
C_i	Capital Invested per Sep i
AR_i	Amortized Costs per Sep i
$ACapital_i$	Annual Capital Costs per Sep i
BU_i	Building Costs per Sep i
$ABuildingC_i$	Annual building Costs per stage i
AMC_i	Annual Maintenance Costs per Sep i
TI_m	total impact of the process m
CF_{RM}	environmental coefficient of the material
CF_{Energy}	emission related to the energy expenditure during the process
$Factor_M$	Conversion Factor from kg to Co2 eq
$Factor_S$	Conversion Factor from kWh to Co2 eq

1

Introduction

1.1 Overview

The Aerospace Manufacturer is a high technology industry that produces aircraft parts, designing, building, testing, selling and maintaining aircraft. Aviation has a major impact on a country's economy, as far as connecting people, faster transport of goods and supplies and cost-effective are concerned [1]. Due to its importance in global trading, aviation has a long history of technology inventions, having invented new materials and sophisticated manufacturing processes which have been applied in other industries, decade after decade. In contrast to mass-production industries, aerospace industry has been focused towards complex and low-volume production [2]. It has been a constant challenge for production engineers due to constant challenges such as environmental performance restrictions, high manufacturing costs and competitive market.

The need to produce smaller, lighter, more complex parts at a low production volume, made the industry develop various techniques. With the advent of Additive Manufacturing (AM), many of these problems have been solved as AM is a parts manufacturing technique that builds 3D objects by adding layer by layer and can be used from various materials, from plastic to metal [3]. It is common for AM technologies to use 3D molding software, where a Computer Aided Design (CAD) sketch is read by the 3D printer, which establishes and adds layer by layer successively, depositing the material in the form of liquid or powder.

AM has been used in aerospace applications. Initially used for rapid prototyping to save time and capital during the development period of new parts, but it also has had a great influence on product design, parts manufacturing and assembly and repair in the aerospace industry [4].

Although the possibilities of AM fascinate material engineers, they present a great challenge for those responsible for qualification and certification. The conventional manufacturing processes for aircraft components are well understood and characterized. Unfortunately AM in its current state still does not possess the needed confidence to those in charge of this industry [5]. This lack of maturity has led engineers to do intensive research on all the benefits and limitations of this emerging technology, to better understand the properties of materials and characteristics of surface treatment, develop software solutions that allow to take advantage of design optimization processes and establish certifications [6].

Increasing awareness on environmental protection is being noticed by aviation industries to develop aircraft with light weight and minimal environmental impact. For this purpose, an environmental impact analysis for each technology used in the cost model is perfomed.

This dissertation was developed to study the economic and environmental impact in the production of metal parts manufactured additively. In this model, the entire manufacturing process is analyzed from the construction of the part to its post-processing and compared to conventional manufacturing.

1.2 Objectives

The main goal of this work is to analyse the cost-effectiveness and assess the environmental impact of two additive manufacturing techniques used in the production of metal parts, Powder Bed Fusion (PBF) and Direct Energy Deposition (DED) process and compared to a conventional method most used in the manufacture of metal parts, forging. Thus, the following objectives have been defined:

- to understand the mechanisms AM technologies, PBF and the DED;
- to analyze and determine all the costs along these two processes;
- to analyze the post-processing of each process.
- to create a cost estimation model that estimates the costs of one part;
- to apply the cost model to a case study and analyse the result obtained and comparison to the conventional model;
- to assess the profitability of each process;
- to study the environmental impact of part production of each technology.

1.3 Thesis Structure

Follows a brief description of what is presented at each chapter:

- Chapter 1 - *Introduction*- Provides a brief introduction on the topic of this work, the goals and also the structure of this dissertation;
- Chapter 2 - *State of Art* - Consists of a detailed review of all fundaments to frame this work. An introduction to the AM technology, its various processes and finishing processes, covering its advantages and limitations. A brief presentation of conventional methods, namely forging.

- Chapter 3 - *An Integrated Cost-Model* - Explains the line of reasoning for the designed models as well as chowcasing the research done. Develop the cost model and explanation of corresponding calculations, formulas and timings estimation needed to implement the cost estimation model.
- Chapter 4 - *Results and Discussion* - Presents the results obtained from the cost model and an evaluation of that data along with a discussion of it.
- Chapter 5 - *Conclusion and Future Work* - Sums up the current work and suggests future directions for further research in this topic.

2

State of Art

This chapter presents some fundamental aspects necessary to the development of this dissertation.

First, it is presented the Additive Manufacturing (AM) technology, the historic perspective, which types of metallurgical processes are used and which new finishing processes developed are applied in AM technology. Secondly, a brief introduction to conventional manufacturing processes, focusing on forging, which is considered to be the conventional method of comparison in this study. In third place, some of the most used finishing processes in metalwork will be analyzed. Finally, a brief theoretical review of the cost models and then an introduction to Life Cycle Assessment is presented.

2.1 Additive Manufacturing Technology

2.1.1 Background

Additive manufacturing is defined as "the process of joining materials to make parts from 3D model data, usually by layer in combination with subtractive manufacturing" [7]. Over the years, AM has taken important steps, mainly in product design, as represented in figure 2.1.

The first steps of AM were in the 1980's, where parts called Rapid Prototyping were developed in a quick way to check their shape, fit and function [9–11]. In 1987, the company "3D systems" developed a plastic processing system known as stereolithografy. This process consists of solidifying thin layers of polymer using a laser Ultraviolet (UV). Since then, many companies researched and made progresses to develop new technologies, improve processing and commercialize them [10, 11].

In the 90's, the bet of several companies allowed the development of other techniques based on polymers such as, Fused Deposition Modeling (FDM), Solid Ground Curing (SGC), Laminated Object Manufacturing (LOM) and Selective Laser Synthesis (SLS) [10, 11]. In addition to the new AM

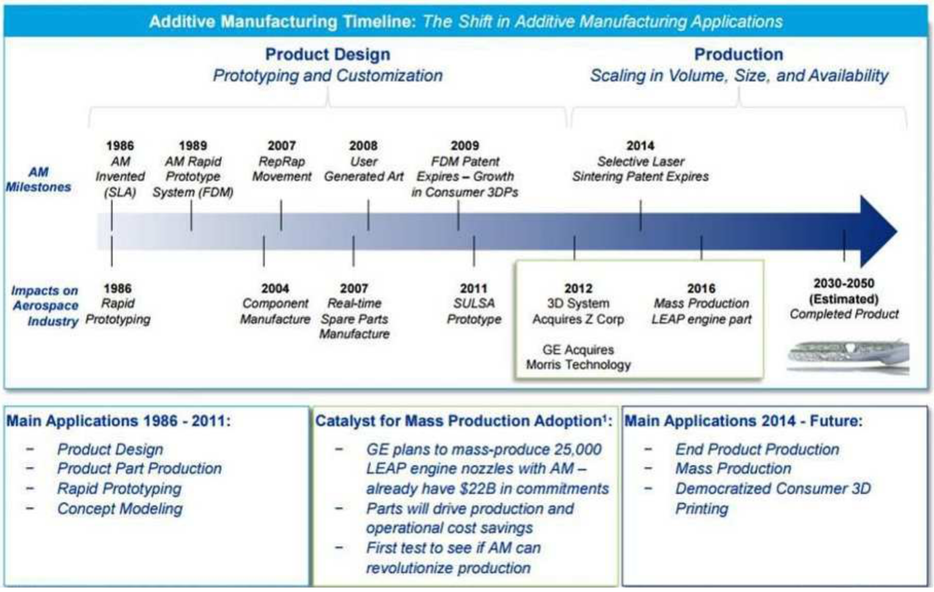

Figure 2.1: AM important milestones

Source: Additive manufacturing paths to performance, innova-tion, and growth[8]

techniques, processes based on metals were initially introduced through laser sintering and only later by powder sintering [10, 11].

The improvement of computers, Computer Aided Design (CAD) software also had a development that came to revolutionize the process, causing AM to take off exponentially in the mid 2000's. The internet had a strong influence on this growth by promoting global interaction [11]. Until the mid-2000's, AM was only possible with plastic softs as the prototyping goal. Since then, with the range of materials increasing sharply, it is possible to create new, stronger and more detailed and functional parts [11].

The AM process is currently applied to almost all market areas, from electronics, aerospace and automobiles to education and medicine. In the aerospace industry, AM has the potential to change the future of aircraft manufacturing, from design to construction. The main aircraft manufacturers are already producing parts with AM, although such parts are still non-critical parts and are doing so only to a limited extention. Such usage of AM results from the aircraft manufacturers strive to reduce the weight of aircraft [12]. Some of the aviation companies already using AM processes are:

- Airbus has already adopted this technology by changing internal components like brackets or cable routing cards from a conventional manufacturing process to 3D printing on its A350 model [13].
- Boeing applied 3D thermoplastic printing for prototypes and components for use on its 737, 747, 777 and 787 aircraft models [14].
- Lockheed Martin and Sicaky created the first propulsion tank through additive manufacturing, as shown in figure 2.2. They used Electron-beam Additive Manufacturing (EBAM) technology to create the titanium tank in raw form that later had to be machined [15].

- NASA is evaluating the use of additively manufactured parts for its next mission to Mars. The figure 2.3 shows a copper rocket engine part additively manufactured, designed to operate at extreme temperatures and pressures [15].
- Aerojet Rocketdyne manufactured and tested a rocket engine thrust cam made using AM deposition from a copper alloy. After manufacture, the part was subjected to several tests, such as the hot fire test shown in the figure 2.4 [15].

Figure 2.2: Titanium Propulsion Tank

Figure 2.3: Copper Rocket Nozzle

Figure 2.4: Testing of an Additive Manufacturing Rocket Nozzle

Source: Additive manufacturing of metals [15]

Aerospace applications require strict certified procedures for processes and components. Reducing the weight of an aircraft can result in significant savings during launch into space, escaping the earth's gravitational pit or fuel savings during commercial aircraft flights. The reduction of material waste during the manufacture of expensive special materials, such as nickel and titanium based alloys, is also an important factor to justify the use of AM.

Some authors believe that the results of AM in the aviation industry are livable and that in the near future the industry can have an aircraft almost 100% manufactured with AM [14, 16]. However, not everyone agrees that AM will be able to overcome the efficiency and agility of the global freight industry.

In a business case study, the Airbus EADS Innovations group carried out an eco-assessment analysis applied to a standard Airbus A320 nacelle overhead support, evaluating detailed aspects of the general life cycle from the supplier of the burdened metal powder, to the equipment manufacturer [15]. This assessment contrasted the costs and savings of each method across the entire manufacturing site, indicating a lifetime cost savings mainly due to the reduced weight. The Airbus Group Innovations team cites another study [15] carried out in which the weight-saving benefits of AM projects in relation to energy consumption and the reduction of CO_2 emissions by almost 40% over the entire life cycle. A savings of 25% in the reduction of titanium scrap and a possible weight saving of 10 kg per aircraft were also mentioned [15].

2.1.2 AM Processing Steps

AM requires some steps of multiple difficulties depending on the part's complexity. The process begins with the creation of a CAD model using a computer software or scanning an existing object.

The software slices the CAD and creates a file with instructions for the machine. Then, the machine creates the object layer by layer by forming each layer via the selective placement. After the building process is completed, the part produced is carefully cleaned and it may have to go through finishing processes, as shown in figure 2.5.

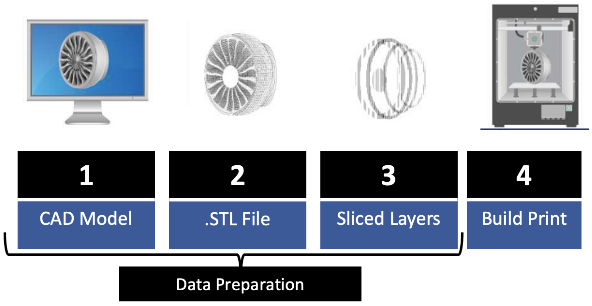

Figure 2.5: Generalized AM process

Source: Cost estimation model for the directed energy deposition process adopting an activity-based approach [17]

2.1.2.A Data Preparation

The AM process must start with a 3D model using CAD software that must contain a precise internal and external description of the object. This file will have to be converted to a language compatible with AM machines [18]. There are several file formats, the most used are Stereolithography (STL) and Additive manufacturing File (AMF). STL transforms a simple model like a square box, where its surfaces can be approximated with twelve triangles. The more complex the surface is, the more triangles are produced. While the AMF is a file format that allows for more details such as colors, materials and constellations [18].

Finally, with the specialized software's help, the file is divided into several transversal layers creating a new Stereolithography Instructions (STI) file [18]. In this last point, there are some aspects to be considered such as the orientation of the piece, supports and support structure.

2.1.2.B Build Print

This is the main stage of the whole process, after the AM machine receiving the file, the part can then be produced. First, the operator must configure the machine by preparing the raw material and determine the process parameters. Then the part's construction is in charge of the AM machine, which is an automated task that requires only the operator's supervision.

Additive Manufacturing is, as the name itself implies, the process that adds material during the production of a part. For which, different technologies are used. Regarding the technologies applied to metal parts, we can classify them in 4 main categories: Material Jetting (MJ), Binder Jet (BJ), Powder Bed Fusion (PBF) and Direct Energy Deposition (DED), each described as follows.

Material Jetting

Material Jetting is a 3D printing process more like conventional 2D printers. In the MJ, a print head distributes droplets of a photosensitive material that solidifies under UV light, forming a layer

[19]. The material used in this technology is thermoset photopolymers in liquid form, as shown in figure 2.6. The steps of the MJ printing process:

1. The resin is heated to 30-60ºC to achieve the ideal viscosity needed [20].
2. The print head travels on the platform and deposits droplets at the designated locations[20].
3. A UV light source fixed to the print head cures the deposited material, solidifying it. Thus, it gives rise to the first layer of the piece [20].
4. After the construction of the first layer, the platform goes down one layer height and the process is repeated until the entire piece is completed [20].

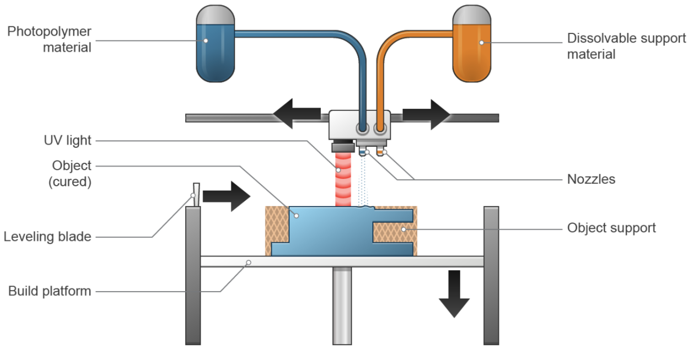

Figure 2.6: Material Jetting

Source: www.make.3dexperience.3ds.com

MJ is classified as a technology capable of producing smooth parts with surfaces compared to injection molding, with a high dimensional precision (in the order of 0.1%) [19, 20]. However, MJ parts are mainly purchased for prototypes given their poor mechanical properties. MJ is an expensive technology making it unviable for some applications [19, 20].

Binder Jetting

Binder Jet, shown in figure 2.7, is a multi-stage AM process developed by Massachusetts Institute of Technology (MIT) in the early 1990's [21]. This 3D printing process uses a powder-based material and a binder. An impression involves several processes:

1. The powder material is spread on the construction platform using a roller [22].
2. The print head deposits the bonding adhesive on the powder, when necessary [22].
3. The construction platform is lowered by the layer thickness of the model [22].
4. Another layer of dust is spread over the previous layer. The object is formed where the powder binds to the liquid [22].
5. The process is repeated until the entire object is made[22].

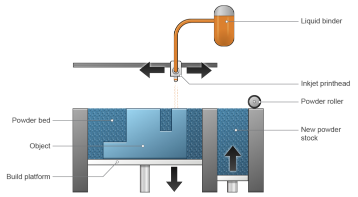

Figure 2.7: Binder Jet Machine

Source: www.make.3dexperience.3ds.com

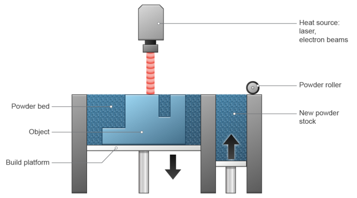

Figure 2.8: Powder Bed Fusion Machine

Source: www.make.3dexperience.3ds.com

BJ allows a wide variety of colors and allows the use of raw materials such as metals, polymers and ceramics. However, due to the use of binder, the parts are not suitable for structural parts. [21, 23].

Powder Bed Fusion

Powder Bed Fusion methods use an electro or laser beam to melt and melt the metal powder. In the figure 2.8 we can see a schematic of a PBF machine. Building a part with PBF requires the following steps:

1. A layer of metallic powder is spread on the platform.
2. A laser melts the first layer.
3. A new layer of powder is spread on the previous layer using a roller.
4. More layers are spread, fused and added.
5. The process is repeated until the part is fully created.

This process has several techniques for melting metal powder such as: Direct Metal Laser Sintering (DMLS), Electrical Discharge Machining (EDM), Selective Heat Sintering (SHS), Selective Laser Melting (SLM) and Selective Laser Synthesis (SLS), each described as follows.

- DMLS, was developed by Germany's Electro Optical Systems (EOS). This printing technique fuses very thin layers of metallic powder using a Ytterbium fiber laser beam. The system operates in a protective atmosphere of nitrogen and argon allowing the use of a wide range of metals [24]. DMLS has an excellent and precise resolution in the creation of its objects, being used for the construction of prototypes of instruments, instruments and objects for the aeronautical and space industry [25].
- EDM developed by the Swedish company Arcam, builds the pieces layer by layer by melting the metallic powder through an electron beam. When electrons reach the metallic powder at high speed, the kinetic energy is converted into thermal energy by melting the metallic powder [24]. The high quality of finish allows this process to become standard for medical applications and parts construction for aircraft [26].

- SHS uses a heated thermal printing head to melt the powder material. The use of this thermal head and not a laser permanent the necessary electrical energy. The process is used for prototypes producing and not to final application parts [26].
- SLM uses a high-power iterbium fiber laser to fuse or metallic powder [24]. A roller or blade is used to spread the powder, which is then melted by the laser, building the piece in layers. It is a relatively fast process that requires the use of an inert gas and has high energy costs [26]. This technique is used for dental application and for turbine blade with internal shaped cooling channels, vane segment in aerospace applications. [24]
- SLS and SLM have the same principle, differing only in that the SLM achieves a complete fusion of the powder layers and the SLS does not [27]. The SLS process benefits from having no additional support structure and from monitoring the temperature of layers by automatically adapting the laser power. Both models have a cooling period to guarantee a high tolerance and quality of fusion [26].

Directed Energy Deposition

Direct Energy Deposition is a collection of processes that uses thermal energy, laser or electron beam, focused on melting and bonding materials in the form of powder or wire, as shown in figure 2.9 [28].

This process has two techniques for melting metal: Laser Metal Deposition (LMD), Electron Beam Melting (EBM) and Laser Engineered Net Shaping (LES). The systems can also be powered by a metallic wire or metallic powder. The powder-based DED deposits layers of powder through a nozzle by melting it with a laser or an electron beam. The wire-based DED systems deposits the wire through the nozzle and create a molten well with a laser.

The process can be used with polymers, ceramics but it is with metals that DED together with PBF are the most reliable and used AM techniques. Almost all weldable metals can be printed with DED. This includes titanium and its alloys, inconel, tantelo, aluminum, amongst others [28, 29].

A typical DED machine consists of a nozzle mounted on a multi-axis arm, which moves in 4 or 5 directions, which deposits the material by melting on the specific surface where it solidifies, as shown in figure 2.9. DED consists in the following steps [30]:

1. The arm with the nozzle moves on the printing platform.
2. The material is deposited by the spout on the platform's surface.
3. The material is supplied in the form of wire or powder.
4. The material is melted using a laser or electron source after deposition.
5. More layers are added until the object is finished.

DED presents itself as a fast and inexpensive AM technology compared to the others. However, fusion processes require more research and improvement as well as require post-processing to achieve the desired effect [31].

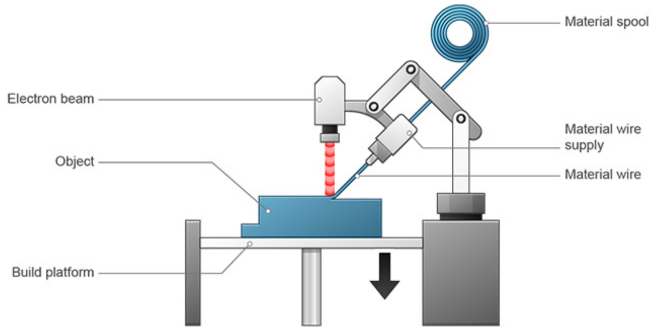

Figure 2.9: Direct Energy Deposition
Source: www.lboro.ac.uk

2.1.3 Capabilities and Challenges of Additive Manufacturing

AM is widely adopted in many industrial sectors, particularly in the aeronautical sector. The main companies in the world are converting to this technology but not abandoning the convencional manufacturing in the production of their parts. It is important to note the main differences and limitations of this technology, as explained in the brief description presented:

- ***Overall*** - Although AM already works with a wide variety of raw materials, its results still have a high degree of uncertainty. Therefore, its use is limited to parts that provide little mechanical effort, since deposited layers can create weakened parts if they are not perfectly calibrated [32]. The total density of AM metal parts is not possible without the subsequent Hot Isostatic Pressing (HIP).
- ***Design Complexity*** - Parts with more complex geometries and internal cavities are a limitation of conventional manufacturing. With conventional techniques it is difficult to produce objects with a high complexity and detail and sometimes they have to be subdivided into several less complex parts, which is avoided by AM that produces the piece as a whole [33]. With the tools of advanced software and AM brought the possibility to produce uniform parts with complex changes geometries and high internal and external resolution [34].
- ***Part Size*** - AM has restrictions on the size of the parts. The size of the objects is limited to the size of the machine's printing chamber. Producing large chambers for AM machines is expensive, since inert atmospheres or vacuums are required. On the other hand, AM allows you to produce very small parts with high detail [35].
- ***Timings*** - Many AM machines distribute the material at a speed of five cubic inches per hour [36]. Depending on your desired final shape, it can take 2-3 hours to produce a shape that conventional PM could make in 5-10 seconds [37].
- ***Short waiting time*** - Engineers can create a prototype immediately after finishing the part's STL file. Once the part is printed, engineers can start testing its properties instead of waiting weeks or months for a prototype or part to arrive [36].

- ***Weight Parts*** - AM makes it possible to produce complex parts with optimized structures which make the parts lighter. This is a great advantage, especially in the aerospace industry as the weight of the aircraft is an important factor for engineers [38].
- ***Tooling*** - The comparison of 3D printing to the traditional manufacture of electronic components researched in Italy found out that 93.5% of the cost of manufacturing a product using the traditional method is linked to tools [39]. A strong advantage of AM is the ability to significantly reduce or eliminate the use of tools.
- ***Material Waste*** - Traditional methods generate a significant amount of waste. However, with AM only the amount of raw material needed to produce a product is used. Thus reducing waste with 3D printing will also have a positive impact on the environment [39].
- ***Manufacturing*** - In the conventional method the production of the pieces is done in several places and then stored, after which they can be distributed when necessary. With AM, parts are produced and stored simultaneously in the same factory according to the market needs. It allows the possibility of reducing inventories, as it is possible to produce parts in remote locations on demand, eliminating large warehouses of stocks and the need for transportation [40, 41].
- ***Cost Prodution*** - 3D printing offers a good solution for manufacturing small quantities. Forging requires a large investment in die and custom tools not being economically profitable for low demands [39]. On the other hand, AM does not offer economies of scale [39].
- ***Produts Quality*** - AM technologies still have some quality limitations in terms of tensile stresses and construction resolution in the same technology cases, with significant surface roughness. In contrast, forging is a much more developed and studied method with reliable and known results [40].
- ***Finishing Equipment*** - The parts produced with AM when compared with the parts produced with conventional method have greater roughness and purity, forcing the need for post-processing [32]. To eliminate the roughness characteristic of AM technology, surface treatment using a grinder or shot peening is necessary. For parts produced using powder, they have purity that will have to be treated with a HIP that will reduce the purity and increase the part's resistance [42]. Particular to PBF, is the use of supports in printing that after printing have to be separated from the part that can be removed with a water bath if they are soluble or cut using cutting tools if they are insoluble in water.
- ***Raw Materials*** - Currently, AM parts still have little variety of materials available. Despite the constant innovation and research in this new technology. The truth is that the raw materials associated with AM are still scarce [43]. Forging on the other hand has a greater variety of raw materials available.

Alll things considered, AM still needs further research in order to be able to compete with the conventional techniques currently in market, nevertheless AM is already market ready as it has been stated.

2.2 Conventional Manufacturing

For the purpose of case comparison and evaluation of the impact of AM in this industry, a basic understanding of how traditional methods work is necessary. In this chapter, some of the most used conventional methods are presented, with emphasis on forging, one of the most used techniques in the aerospace industry, that will serve as a comparison to the model being developed in the present thesis.

Since the industrial revolution, various techniques have been developed to optimize manufacturing processes. Nowadays, there are several technologies in which we can classify into three major groups: AM, presented before 2.1, machining process and forming process [44].

2.2.1 Machining Process

The machining industry together with forming have in common the controlled removal of material, also known as subtractive manufacturing. The discovery and handling of new cutting tools was an important advance in the last century for metal cutting technologies. Today, this type of metal fabrication plays an important part in the economy.

Machining is the process where the operating conditions are most varied. Almost all metals and metal alloys can be machined, whether they are more hard or soft, cast or wrought, ductile or brittle [45]. Machining encompasses a set of processes in which a piece of raw material is cut successively until it reaches the required shape and size. Metal cutting can be grouped by the physical phenomenon used:

- Chip forming - Sawing, drilling, milling, etc
- Shearing - Punching, stamping, scrissoring, etc
- Abrading - Grinding, lapping, polishing, etc
- Heat - Flame cutting, laser cutting, plasma cutting.
- Electro-chemical - Ectching, EDM

2.2.2 Forming Process

Formative manufacturing is a process of machining metal parts through mechanical deformation. The shape of the piece is acquired without adding or removing material, and its mass remains unchanged [46]. When flatrolled sheets became commercially available, the final products were manufactured, formed, and shaped by hand. Gradually, machines, particularly presses, replaced most of the hand forming techniques [47].

Training processes tend to be categorized by differences in effective tensions. These categories and descriptions are highly simplified, since the stresses operating at a local level in any process are very complex and can involve many varieties of stresses operating simultaneously. In figure 2.10 the four types of categories within the forming are outlined.

- Bearing, where the material is passed through a pair of rollers;
- Extrusion, where the material is pushed through a hole;
- Matrix formation, where the material is stamped by a press around or on a matrix;
- Forging, where the material is shaped by localized compressive forces.

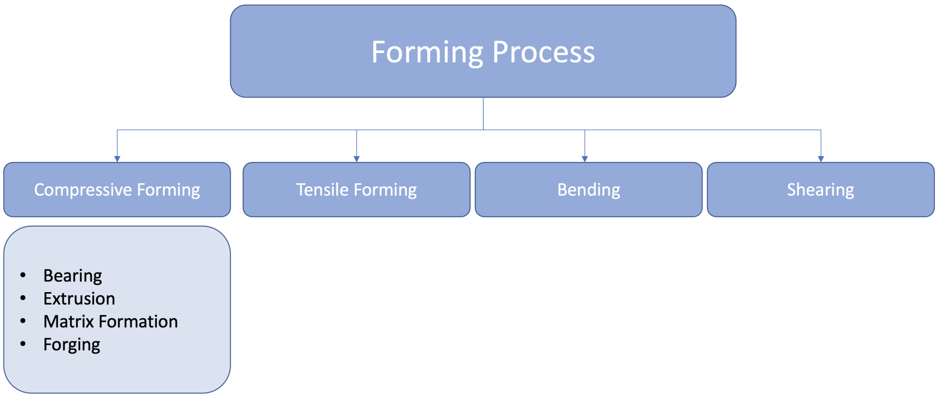

Figure 2.10: Forming process

The rest of the processes are usually used in conjunction with the compressive forces. Traction forming involves those processes in which the main means of plastic deformation is the uni or multiaxial tensile stress. This category of forming processes involves those operations where the main means of plastic deformation is a bending load. This category of forming processes involves those operations where the main means of plastic deformation is a shear load.

2.2.2.A Forging Process

In the last 100 years, not only new types of machining equipment have been developed, but also new materials with special capabilities. In 1930, the first forging press appeared. At the time with the appearance of motor vehicles by Henry Ford, the demand for forgings increased significantly, leading the National Machinery Company to invent Maxipress which increased the production rate and with a lesser degree of difficulty [48].

The emergence of electrical power and technological advances, computer-controlled hammers and presses are capable of making a wide range of components in a variety of materials for many applications, including aerospace, automotive, mining and agriculture, among others. Recently, the automotive and aerospace industries account for about 50% of US production using forging techniques [49], as shown in figure 2.11.

Globally, the commercial segment represents around 51 % of the aerospace industry in the United States of America (USA), as seen in figure 2.12, due to the increasing demand for air passengers for

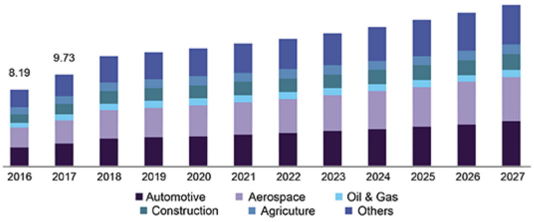

Figure 2.11: U.S. metal forging market size, 2016-2027 (USD Billion)

Source: www.grandviewresearch.com

Asia-Pacific travel over time. The second is the military segment, which is estimated to grow due to the increase of the defense budget, which remains one of the flags of this country [50].

Nowadays, the automotive and aerospace industries account for about 50% of USA production using forging techniques [1], as seen in figure 2.11 [50].

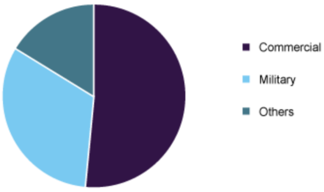

Figure 2.12: Global aerospace forging market share, by aircraft, 2019 (%)

Source: www.grandviewresearch.com

Forging is a process that converts a metal in an object through compressive forces on a discrete part in a set of dies. The process requires a few steps which depend on the complexity of the object to be produced. Figure 2.13 shows the generalized stages of typical forging process, then follows a brief explanation of each process stage.

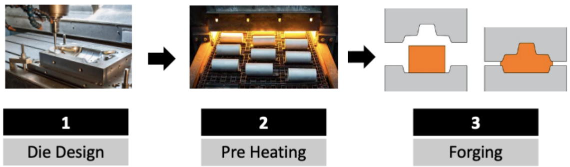

Figure 2.13: Generalized Forging Process

1. Die Design and Design of Forging Parameters

Die manufacturing represents a significant area of production technology, the most restrictive aspect to be considered is the cost of tools. The construction of a metal stamping die requires a high number of resources and people, which will make the die building more expensive, for this reason the bigger quantity of parts produced the more economically profitable it becomes [52].

The manufacture of a die and its ability to produce parts depends on several factors. The main areas of concern are:

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[1] These predictions were made before and during the appearance of the COVID-19 virus. Since the aerospace industry was one of the sectors most affected, they may not be up to date.[51]

- **Parting Line** - The Parting Line is usually the central line, which separates the two dies. For a complex part, designing the parting line may not be a simple task [53, 54].
- **Flash and Gutter** - During the compression of the material against the die, the flash material can flow into a gutter. A good design can prevent an unnecessary increase of the forging load with respect to the excess of flash [53, 54].
- **Draft Angles** - When designing the die, it is necessary to take into account how the part will be removed from the die. Tilt angles are sometimes used to facilitate such removal [53, 54].
- **Fillet** - The fillet is a small radius provided at the corners to ensure smooth flow of metal into the matrix cavity. A small fillet leads to rapid wear of the die and an improper metal slip [53, 54].
- **Die material** - The die must be made of a hard material resistant not only to high temperatures but also to mechanical and thermal shocks, as well as it should be of high resistance to wear [53, 54].

2. Pre Heating

Depending on the temperature at which the metal is forged, the forging can be classified as cold, warm or hot forging, as briefly described:

- **Cold forging** involves forging with open die or close die and use of lubricant close to room temperature. Forgings of carbon steel and standard alloys are commonly cold forged, not requiring this production step. This type of forging offers an economically competitive advantage, since the forged part requires little finishing that normally makes the part more expensive [55, 56].
- **Warm forging** is forging above the ambient temperature to below the recristallization temperature. Compared to cold forging, warm forging has the potential advantages of reduced tool loads, increased ductility, elimination of annealing needing before forging and favorable forging properties that can eliminate heat treatment [55, 56].
- **Hot forging**, is when the metal and the die are heated to the same temperature. The objective of this step is to avoid hardening by deformation, in this way the metal is heated to the recrystallization temperature in such a way that the recrystallization occurs simultaneously with the plastic deformation [55, 56]. Hot forged components have greater ductility, which makes them desirable for many configurations. In addition, as a technique, hot forging is more flexible than cold forging, as it allows for customization of the parts being manufactured [55, 56].

3. Forging

During forging the metal is compressed under high pressure for a part to reach the desired shape. In general, forging can be classified based on how metal flow is confined, as open die or closed die, as shown in figure 2.14.

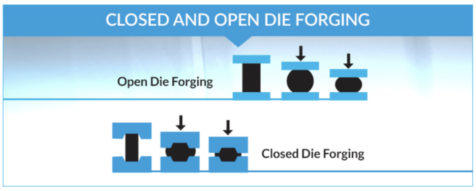


Figure 2.14: Closed and Open Die Forging

Source:www.indiaforging.com

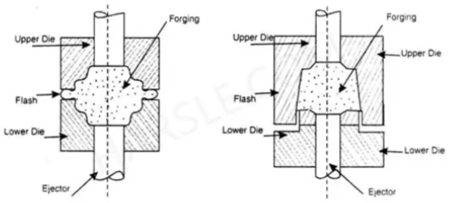


Figure 2.15: Flash and Flashless Hot Forging

Source:www.harsle.com

Forging is the molding of metal by plastic deformation. This process covers a multitude of equipment and techniques. Simply put, forging can be classified as follows:

- Forging temperature - Hot, Warm or Cold Forging;
- Die shape - Open Die Forging or Close Die Dorging;
- Compressive forces - Drop Forging, Press Forging or Rolling Forging.

Both the temperature and the type of die have already been analyzed previously.

As far as of the shape of the die is concerned, forging can be classified as open die forging or close die forging. Open die forging is performed using two flat dies, which are not normally touched, or which allows the material to be released freely in the lateral direction. This type of forging is used for large parts or discs, blocks or bars [52, 53, 57]. In closed die forging or impression-die, the cavity is formed by using two or more dies which the metal is deforming undergoes plastic deformation through the pressure exerted [52, 53, 57].

Usually the design of this product is in a die, where the metal is pressed against it to obtain the desired shape. This metal manipulation is usually done using two methods: Drop forging or press forging.

A closed die can also be selected as flash or flashless, as shown in figure 2.15. The flashless forging allows excess material not to escape through the concavity, while the flash type can occur [52, 53, 57]. The advantage of this forging is that it allows more complex shapes and closer tolerances than forging in the open die. Limiting the ability to produce parts with great detail, or forging prevalent in the metallurgical industry [52, 55].

In the drop forging, forging hammers are used to deform the metal through several impact strikes on the metal surface [53, 58]. During the process, the surface layers of the metal are manipulated in shape. However, the central area of the metal will remain unchanged. In this process, the deformation rate is difficult to control and generally the cost of this product is generally lower, for low production volumes, when compared to press forging [53, 58].

In the press forging a slower and continuous pressure speed is used. The material is shaped evenly, from the surface to the center, making it an advantage over drop forging, as it allows for a stronger and more perfect final product [53, 58]. In this process, the initial costs are much higher than using a hammer, making it more economical for increased production volume. Despite being a lingering technique, another advantage is a more controlled deformation rate that allows a more resilient final product [53, 58].

Roll forging consists of two horizontal cylindrical rollers that form a round or flat bar. This type of forging is used to increase the length or decrease the thickness of the metal bar. This bar is heated and then passed through two rollers that contain patterned grooves and is progressively shaped as it is rolled by the machine [53].

2.3 Post-Processing

Full functionality of a deposited metal part will most often require post-processing and finishing to achieve the desired dimensions and properties. Post-processing operations for metals may require heat treatments, machining operations and access to resources that require specialized precision equipment, expert knowledge and operations beyond simple media blasting, sanding, or coating. The author managed to divide the post-processing into four large groups: heat treatment, hot isostatic pressing, machining (cutting) and surface treatments; all presented in the current section.

2.3.1 Heat Treatment

Heat treatment can be defined as controlled heating or cooling of metals with the goal of changing physical and mechanical properties of the part under treatment. In many cases, as metal parts go through different temperatures during the heating phase, going through heating and cooling cycles alters some physical and mechanical characteristics of parts, with the possibility of having thermally affected parts zones [52, 56].

However, heat treatment can be used for different purposes: to increase the material's resistance and/or to decrease the excess duration, allowing better machining and restoring ductility after an intense cold machining process [52, 56]. Figure 2.16 helps to understand how the heat treatment takes place.

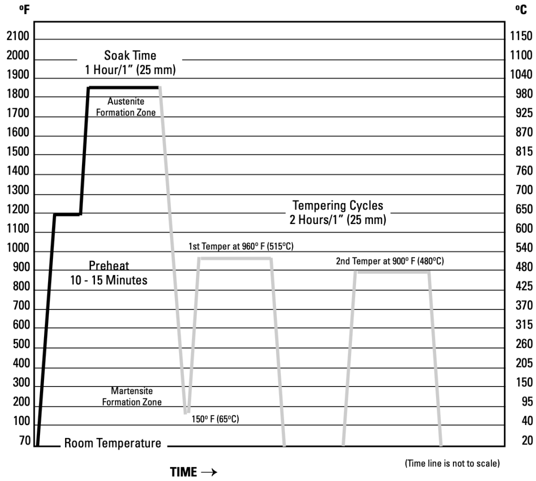


Figure 2.16: Generalized Hot Treatment Steps

Source: Heat treatment, selection, and application of tool steels [56]

Depending on the application of the forged part, the residence times in the oven and the temperature at which the part must be raised are defined. The main heat treatments used in forged metals are annealing, normalization, stress relief, queching and tempering. Such processes are briefly described as follows:

- *Complete annealing* is a very general term that consists of heating the part above the critical zone and letting it cool slowly. Annealing will produce a more refined microstructure to soften the metal to better withstand the constant pressures that the metal may undergo during the machining process [59]. For this reason, this heat treatment is often used not only as a finishing process but also as a preheat use before machining [52, 56].
- *Normalization* is a technique used to offer uniformity in grain size to the piece's metal. When normalized, the piece is heated to a temperature just above the critical point, keeping it there just enough time to form smaller and more uniform metal grains. After heating above the critical point, the part is cooled in the open air until it reaches room temperature. This transformation is called grain refinement, which makes the piece more uniform, but above all improves the strength and toughness of the material [52, 56].
- *Stress relief* is a technique for removing internal stress from a metal. These stresses can be caused many times by the process of cold machining or non-uniform cooling. Stress relief consists of reheating the metal below the critical temperature and then uniformly cooling the part [56].
- *Quenching* involves rapidly cooling the material after heating it above the critical region. After being quickly cooled, the alloy turns into martensite, a hard and brittle crystalline structure. For this reason, after quenching, tempering is normally used [52, 56].
- *Tempering* is used because the martensite steel is very hard but very brittle. Tempering is the heat treatment that seeks to offer the best combination of hardness, strength and toughness. Tempering is effective in relieving tensions caused by cooling, in addition to decreasing hardness for specific intervals [52, 56]. In this process, the metal is reheated to a relatively low temperature with a controlled time, then allowing it to cool in still air.

2.3.2 Cutting Treatment

The cutting treatment may occur in two different ways as explained bellow: wire electric discharge machining or multi axis mills.

2.3.2.A Wire Electric Discharge Machining

Wire EDM is a machining process that emerged in the 1960s with the aim of manufacturing hardened steel die [60]. It is a non-traditional machining process widely used in today's manufacturing industries. It involves removing metal using an electric discharge wire machining the part with high speed and accuracy [61, 62]. This relatively recent technology is commonly used for machining hard materials that are difficult to work with conventional forging.

The process consists of immersing a part in a dielectric which uses a cutting wire powered electrically that cuts the metal, as shown in figure 2.17 [62]. Firstlt, the machines used a Numerical Control (NC), nowadays they use Computer Numerical Control (CNC). This technology has brought several benefits, since it allows the cutting of very hard materials without them being subjected to excessive pressure from the impact used in machining. It also allows achieving high design tolerances [60].

2.3.2.B Multi Axis Mills

Multi Axis Mills is a process that involves a tool that moves in 3, 4 or 5 different directions depending on the type of machine. This machine, as shown in figure 2.18, allows the milling of excess material with a water jet or laser cut [60].

In the most recent machines, a CAD is used through computer software that allows the machine to know where to cut. This technology allows a better finishing of the piece for more complex pieces with increaed detail [63]. Since the machines are using a software which provides the precise indications of cutting the part, then this can be replicated hundreds of times and each product will be exactly the same, in addition such machines only require supervision of the process.

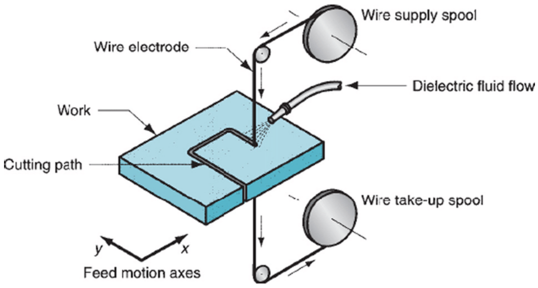


Figure 2.17: EDM Cutting Process

Source: Comprehensive materials finishing [64]

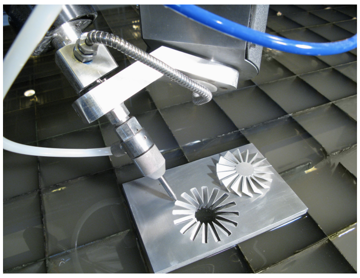


Figure 2.18: A 5-axis Multi Axis Machine and a part manufactured with it.

Source: www.wardjet.com

2.3.3 Surface Treatments

Thermochemical treatment and grinder are the existing surface treatments.

2.3.3.A Thermochemical Treatment

This treatment aims to change the surface properties of the metal. In general, materials with high hardness have a high resistance to wear, but low toughness and resistance to impact. In some parts, a tough core and a wear-resistant surface are desired. For this reason, low carbon steels are subjected to thermochemical treatment by carburizing, which increases the carbon content on the surface, increasing its resistance to wear, while preserving the properties of the core. The means to carry out the treatment are carbon or nitrogen sources which can be in the form of solids, liquids or gases [65]. The process consists of combining repeated heating and cooling, keeping the material in contact with Carbon or Nitrogen, such as specific salts, oils or gases for that purpose [65].

2.3.3.B Grinder

Grinding is an important metal machining process. The process allows for a finer finish and increase the useful life of the part [60, 66]. With the interaction of abrasive grains on the surface of the part, metal removal occurs 2.20. This removal occurs by a shearing process in which it normally involves a rotating wheel with abrasive particles on the metal surface, as shown in figure 2.19 [60, 66]. Today, the process can be used through an axis machine using a CNC. Several machines are used in this process, such as Whetstone, power tools such as angle grinders and bench grinders.

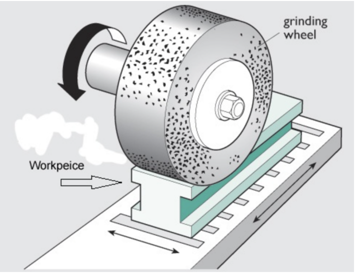


Figure 2.19: Grinder Rotating Wheel

Source: www.surfacegrindingmachine.wordpress.com

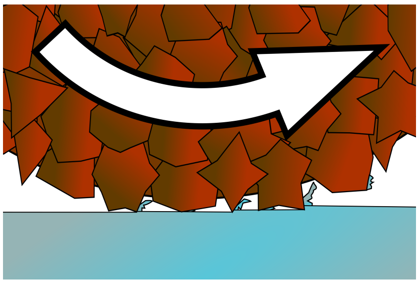


Figure 2.20: Abrasive Process in Grinder

Source: www.wikipedia.org/grinder

2.3.3.C Shot Peening

Shot peening is a cold working process used in the aerospace and automotive industries [67]. Surface treatment procedures such as grinding, milling, bending or heat treatment cause residual tensile stress. This residual tensile effort leads to a reduction of the life cycles of the involved parts. Shot peening converts the residual tensile stress into residual compression stress, which allows to increase the complexity of the service life and maximize the load supported by the parts [68].

Shot peening is used for better resistance to metals' fatigue. It consists of bombarding small hardened spheres, usually steel, against a surface of the object creating small plastic deformations on the part's surface, causing changes in the mechanical properties [67, 68]. The impact of each shot particle on the object generates a compression stress on the surface of the piece. A surface notched by the ball generates a compaction force below the notch. Hammering generates not only one but severals notches on the surface, forming a layer of residual compaction stress on the part [67, 71].

The creation of the residual compression stress created on the part's surface helps to prevent the appearance of cracks as they cannot propagate in the compression environment generated by hammering [67, 71].

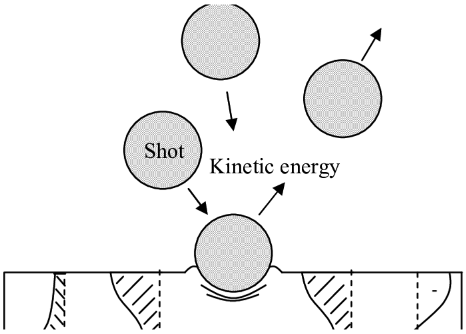


Figure 2.21: Compression Stress

Source: Texture Gradients in Shot Peened [69]

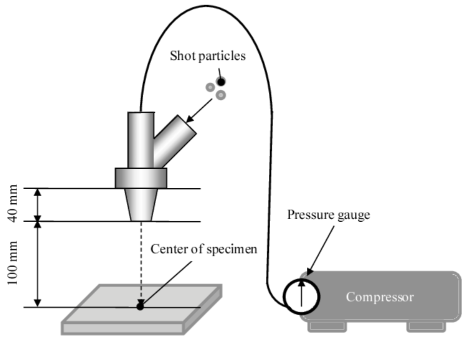


Figure 2.22: Shot Peening Machine

Source: Modelling of particle behaviour in shot peening process [70]

2.3.4 Hot Isostatic Pressing

Hot Isostatic Pressing (HIP) is a post processing method used to reduce porosity of metals and increase the density of ceramic materials. The process consists of placing the object into a chamber where it is pressed on all sides with equal pressure (isostatic pressure) and with an elevated temperature for consolidation in a dense solid, as represented in 2.23 [72]. HIP applies high temperatures from several hundred to 2000 and isostatic pressure from several tons to 200 MPa at the same time. Argon gas is the most used for the pressure medium. The gas lays at 1000 and under the pressure of 98 MPa can cause an intense convection corrent due to the high density, viscosity coeficient and high thermal expansion coeficient [73].

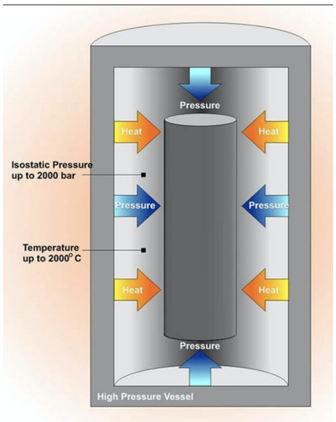


Figure 2.23: HIP process

Source: www.azom.com

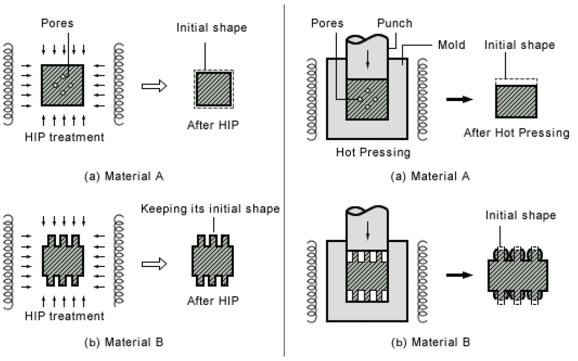


Figure 2.24: HIP vs conventional compression

Source: www.kobelco.co.jp

Through HIP it is possible to obtain material formats not very different from the initial one after high pressure is applied, contrary to what happens with hot pressing, as shown in the figure 2.24 [72].

HIP is used for wide range of purposes:

- Pressure powder sintering;
- Diffusion connection of different types of materials;

- Removal of residual pores in sintered items;
- Removing internal defects in castings;
- Rejuvenation of parts damaged by fatigue or creep;
- and High pressure impregnated carbonization method.

2.4 Cost Modelling

Over the years, mass production factories have been migrating to developing countries such as China and India. Large American and European companies have been forced to rapidly shift production to lower volumes of innovative and sustainable products with high added value. Due to the need of greater flexibility and low-cost volume production, manufacturers have been looking for tools and new techniques. One of the emerging techniques is additive manufacturing. AM allows for freedom of design, removal of tool requirements and good profitability for low economic volumes. [3]

The continuous comparison between conventional manufacturing methods and AM has been a constant issue for companies and production engineers. 3D printing of metallic hair combined with the part's redesign has a positive impact on cost savings [74]. There are two ways to assess the costs of additive manufacturing:

- The first is to study under what circumstances AM is competitive in relation to traditional methods [75]. In this analysis, it is not only important to assess the production costs of the part, but also the economic impact that the part will have in all of its life cycle. For example, a part adapted with AM that at the outset of its production is more expensive than the same part by a traditional method, can be profitable in the long run, if it has a weight reduction of 18% which will allow a savings aircraft fuel tank.
- The second approach is to compare different AM technologies. It is important to know which are the most profitable for each situation, not only in the build print process but also the post processing involved.

The first development of cost modelling of AM was launched in 2003 by Hopkinson and Dickens [76]. The authors calculated the cost of producing an integrated part by AM based on 3 premises [77]:

1. the system produces a single kind of part for a year;
2. uses maximum volumes;
3. and the machine operates 90% of the time.

In this model, costs can be divided by machine, labor and material costs, with energy and building costs being practically neglected accounting only for 1% of total costs [75, 77]. The authors report the cost estimate using the traditional injection model method with Laser Sintering (LS), FDM and STL in

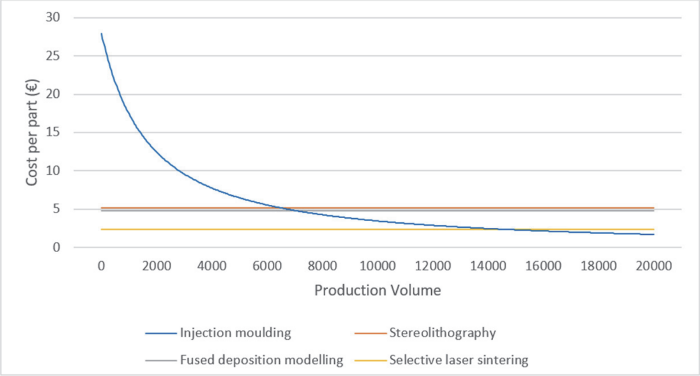


Figure 2.25: Cost comparison for the lever by different processes

Source: Cost models of additive manufacturing: A literature review [77]

terms of costs by various quantities, as shown in figure 2.25. This model is a good approximation, but it is only validated when production volumes of the same part is high.

Later, in 2006, according to Ruffos [78], a study based on the total cost, dividing them into labor, material, energy, administration and general costs [75, 79] was published. In contrast to the previous cost model, developed by Hopkinson and Dickens, Ruffos' cost model has a curve that relates the cost per part to the volume of production and has the shape of a sawtooth, as shown in figure 2.26 [79].

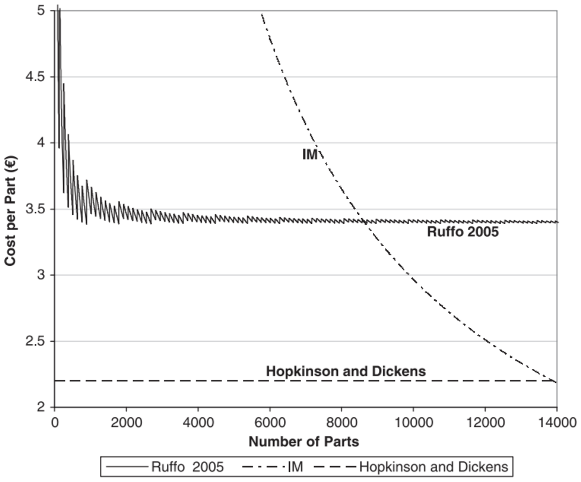


Figure 2.26: Cost model comparison of LS and Injection Moulding (IM)

Source: Cost estimation for rapid manufacturing ' simultaneous production of mixed components using laser sintering [79]

The Hopkinson and Dickens model was compared with that of Ruffos, now a comparison of evidence reveals an underestimation of the Hopkinson and Dickens model [75, 79]. Hopkinson and Dickens and Ruffos were the first to develop cost estimates for AM. However, both authors developed models where they did not take into account the post processing of the parts, only considering the manufacture of the part. Over the past decade, more complete new models have been developed. It is possoble to find quite complete models for certain production steps or for a specific production line.

Each part has a set of production steps depending on its purpose and on the method used for its construction. A part produced with forging does not have the same post-processing as a part produced by AM. Like a structural part, it does not have the same post-processing as a prototype part. In this way, a flexible model where the editing of the production line of that particular part is allowed is required so that the designed model can better comply with the market reality.

Therefore, the development of a cost model where the stages of manufacture can be selected is an important goal that has not been achieved yet and this is a gap extremelly important to fill in.

2.4.1 Process-Based Cost Modeling

In this work, the process-based management principle is adopted. As the name implies, Process-Based Cost Modeling (PBCM) is a fusion of the cost model and the process. The model was developed to answer to the gap between technical and financial understanding in the market. Process engineers are generally concerned with optimizing physical parameters to improve product and process performance, however these adjustments affect the cost of production [80].

PBCM is a sequential approach to cost in stages for the production of a given object. Nowadays, PBCM has been used to make process decisions that range from the production and assembly of automobiles [81, 82] to the project and manufacture of electronic chips [83, 84].

The PBCM standards are based on a detailed simulation of each process. The first step is to identify the most important cost elements for each stage (such as material, labor, energy, capital and construction space) to achieve the desired annual production. Secondly, it is estimated as a resource of the producer (cycle times per stage, machine performance, down times, among others). Finally, the production model is transformed into a cost model simply by multiplying each entry by a price (raw material price, electricity price, building, among others).

Hence, the PBCM consists of three main parts: decision rules, inputs and model architecture. Decision rules can be described as a set of mathematical equations that relate to design decisions and their consequences for the process. The model inputs are based on production equipment, interviews with a specialist to identify values for these input values and based on theoretical research. At last, the model architecture allows editing of the production steps, selecting or removing production steps for a given case study.

2.5 Life Cycle Assessment

2.5.1 Introduction

The importance of preserving nature is a currently important topic in today's society. In the 1960's, with the increased consumption of manufactured products and the oil crisis, society started to question the extraction limit of natural resources and the developmental model and its validity as a solution in search of the satisfaction of consumption needs of mankind [85]. The first studies aimed to calculate the energy consumption spent on the extraction, manufacture or service of a given process. These studies involved the elaboration of a process flow chart with the balance of mass and energy [85].

The interest in the study of Life Cycle Assessment (LCA) has reappeared due to the Growing environmental concerns. The sustainability of products and services has became mandatory for companies and, amongst the various ways of measuring sustainability, the LCA is the most matured method [86]. The LCA is a tool that allows us to assess the potential environmental impact associated with a product or activity during its life cycle. It also allows us to identify which stages of its life cycle have a more significant contribution to the environmental impact of the process [85, 86].

The general categories of environmental impact considered in a LCA study include the use of natural resources, implications for human health and ecological consequences. The LCA study is divided into four phases, as shown in figure 2.27:

- The definition of the objective and scope;
- The Life Cycle Inventory Analysis (LCI);
- The Life Cycle Impact Assessment (LCIA);
- The life cycle interpretation.

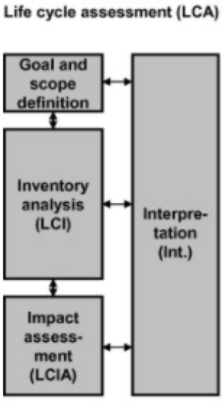


Figure 2.27: Phases of Life Cycle Assessment

Source: Towards a methodological tool for the integral evaluation of the sustainability of a biocomposute material: a case study [86]

2.5.2 The Goal And Scope Step

This step consists of the definition of the context of the study, description of the product system in terms of the functional unit and the limits of the system, as shown in the figure 2.28. The functional unit is a quantitative reference unit for all flows of inputs and outputs in the LCA [85, 86].

2.5.3 Life Cycle Inventory Analysis

LCI involves the data collection and calculation procedures needed to quantify relevant inputs and outputs from a product system [86].

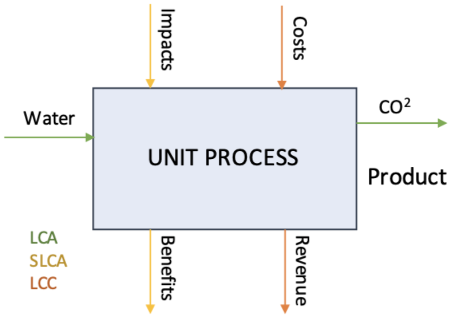


Figure 2.28: Data collection related to every unit process derived from the functional unit

Source: Towards a methodological tool for the integral evaluation of the sustainability of a biocomposute material: a case study [86]

The data is then used to elaborate a flowchart of the study system so that the processes are evaluated and well defined, as well as its boundaries and techniques. This data is then compiled while the environmental loads of the system are calculated and related to the functional unit [85].

There are databases available, for example, ECOinvent, which is a database for LCA providing information on environmental impact [85].

Some databases - such as ECOinvent - provide the LCA with information on the environmental impact from the extraction of the raw material, to the manufacture and use of the part.

2.5.4 Life Cycle Impact Assessment

This phase aims to understand and assess the magnitude and significance of the potential impacts for a product system throughout of life cycle [86].

In this stage, the data is interpreted in terms of environmental impact. In the first phase, categories are assigned to the inventory data. In the next step, the inventory data is then multiplied by an equivalence factor for each impact category. Then, all the parameters included in the impact category are added up and the result of the category is obtained [85]. LCIA can also include optional elements, such as:

- Normalization - the calculation of the magnitude of the category's results in relation to a reference value [85];
- Grouping - assigning impact categories to one or more sets, for example, high, medium or low impact [85];
- Weighting - different environmental impacts are weighted together, generating a single number that represents the total environmental impact of that system [85].

2.5.5 Life Cycle Interpretation

In this stage, the results of the inventory analyses or impact assessment are evaluated to reach conclusions and recommendations [86]. According to ISO140431 (2000), the interpretation must conclude [85] the following aspects:

- the identification of the most significant environmental impacts;
- the assessment of the environmental study for completeness, sensitivity and consistency;
- the conclusions and recommendations for possible improvements to reduce the most significant impacts.

2.5.6 LCA Applications

LCA is a method that deals with complex environmental issues, and presents results in numerical form that allow decisions with more objective bases [85]. The LCA is used to:

- Manage and preserve natural resources;
- Identify critical points in the processes of a system;
- Optimize systems;
- and Optimize mechanical and / or electrical recycling systems.

The LCA also serves for a more complete analyses of the life cycle as a whole of a product. Combined with an analyses of the Life Cycle Cost (LCC), the Social Life Cycle Assessment (SLCA) and a barrier anaylses, it is possible to provide a more detailed analyses of the entire life cycle of a product, **ILCSA!** (**ILCSA!**) from the resource extraction to the end of its life, as shown in figure 2.30 [85].

We can also combine LCA, LCC, SLCA and barrier analyses to obtain more detailed analyses related to the entire life cycle of said product – that is, from the resource extraction to the end of its life – as shown in figure 5.4 [85].

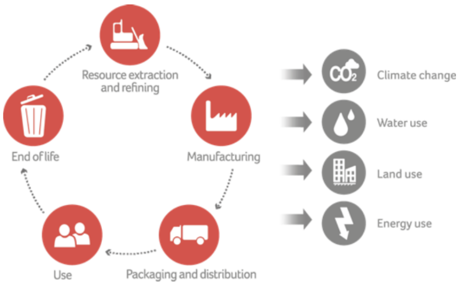


Figure 2.29: Life Cycle Thinking

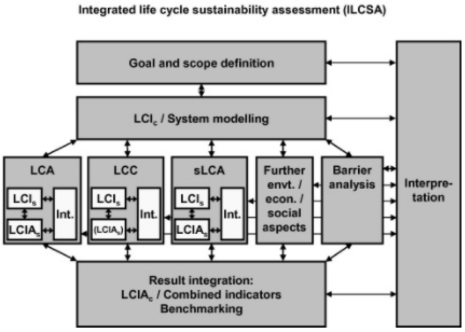


Figure 2.30: Integrated life cycle sustainability assessement (LCSA) methodology

Source: Towards a methodological tool for the integral evaluation of the sustainability of a biocomposute material: a case study [86]

2.5.7 The ReCiPe Model

The ReCiPe method was developed in 2008 through a collaboration between RIVM, Radboud University Nijmegen, Leiden University and Pre Sustainability. It also allows us to assess the impact of said product's life cycle on the environment [87]. The impact is translated in data and resource extractions, such as characterization factors and indicators, that constitute a limited number of scores [88]. There are two ways to derive characterization factors, a midpoint or an endpoint. The ReCiPe calculation:

- 18 midpoint indicators;
- 3 indicators of an endpoint.

Midpoints focus on unique environmental problems such as climate change or acidification for example [88]. The final indicators show the environmental impact at three higher levels of aggregation:

1. Effect on human health;
2. Biodiversity;
3. Shortage of resources.

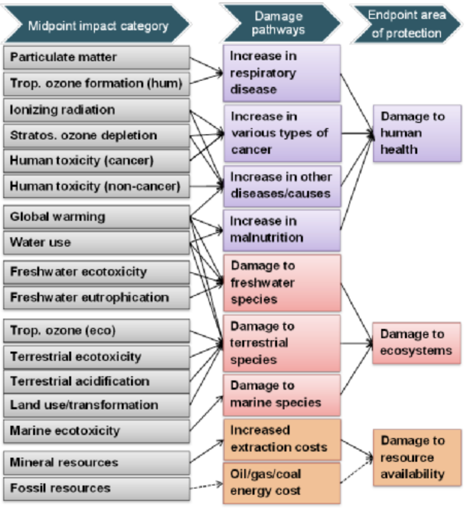


Figure 2.31: Overview of structure ReCiPe.

Source: www.rivm.nl [88]

Despite providing objective data, there can still be some level of uncertainty in the use of the ReCiPe method. In those cases, the user can choose between three different perspectives that affect the LCIA's score. The prospects are based on the following types of assumptions [89]:

- Individualist perspective - Based on short-term interests and technical optimism;
- Hierarchical perspective - based on the most common policy principles;
- Equalitarian perspective - based on long-term precaution and with a safer attitude towards types of impact not fully established.

3

An Integrated Cost-Model

This section presents the methodology, showing all the steps of the development of this dissertation and an analyses of the cost related to the manufacture of parts using the two different Additive Manufacturing (AM) process used in the production of metal parts, Powder Bed Fusion (PBF) and Direct Energy Deposition (DED) and a set of post-processing. In order to have a comparison term, the cost model was extended to a conventional production method of forging.

Throughout this chapter it is explained how the cost model was built and which decision rules are applied to determine the cost of manufacturing for each process. A Process-Based Cost Modeling (PBCM) model was developed involving the study of each stage of production of the part. In general, four main states are required for each process: Build Preparation, Manufacturing, Finishing and Quality Control. Such stages can be divided in diferents sub-stages depending of each manufacturing method.

At the beginning of this section, it is presented how the estimation of a set of parameters for each sub-stage is made. Then, a set of rules and equations is presented to predict the cost of the same part for each of the processes.

3.1 Methodology

After intensive research in the manufacturing on the aerospace industry, analyzing what has already been done and what can be improved and optimized in this industry, it was concluded that many companies in this branch are studying the possibility to use AM in the them processes. Being a relatively recent technology, companies need to understand all the limitations about these AM technologies, knowing how to delineate its advantages and profitability in comparison with conventional manufacturing techniques.

Over the past few decades, some cost models have been developed. These were static models as they do not allow the modification of the production line or present only a cost projection for the manufacturing of the part without taking into account the post-processing necessary to optimize the final characteristics. Working these model limitations, developing a dynamic model where it is possible to edit and customize a production line and compare directly with a conventional method emerged as a need to fully understand the economic limitations of these new technologies.

The most critical parts of the aircraft are support or engine parts made by metals, the focus of this study is the additive manufacturing of metallic parts, namely the two most used technologies in the production of metallic parts the DED and PBF.

A search for existing models was made previously, which should be noted the model developed by colleague Engineer Diogo Sequeira [6] in his dissertation in which he made a cost model for the PBF where he did not take into account the post-processing. On the other hand, it was found that there was no relevant cost model for DED technology. Also, it is necessary to compare the results obtained for AM with a conventional method. Forging being the most used and most comprehensive traditional method within the cost models already developed, it is important to highlight the work developed by Roca et al. [80].

In order to achieve the final objective, a integrated cost model was built in Matlab where the Sequeira model [6] for PBF was used and a new root model was developed for DED and post-processing and compared with a model developed in parallel for forging. The developed model allows selection of all manufacturing processes for a given case study, thus making it an unique dynamic model with much clearer cost estimates.

With the growing need for environmental protection, the environmental assessment was also performed as part of the Life Cycle Assessment (LCA).

With the growing need for environmental protection, a parallel study was carried out on the environmental impact of the technologies studied in the cost model. We calculated the amount of equivalent CO2 emitted into the atmosphere using the mass and energy calculated in the cost model, as presented in figure 3.1.

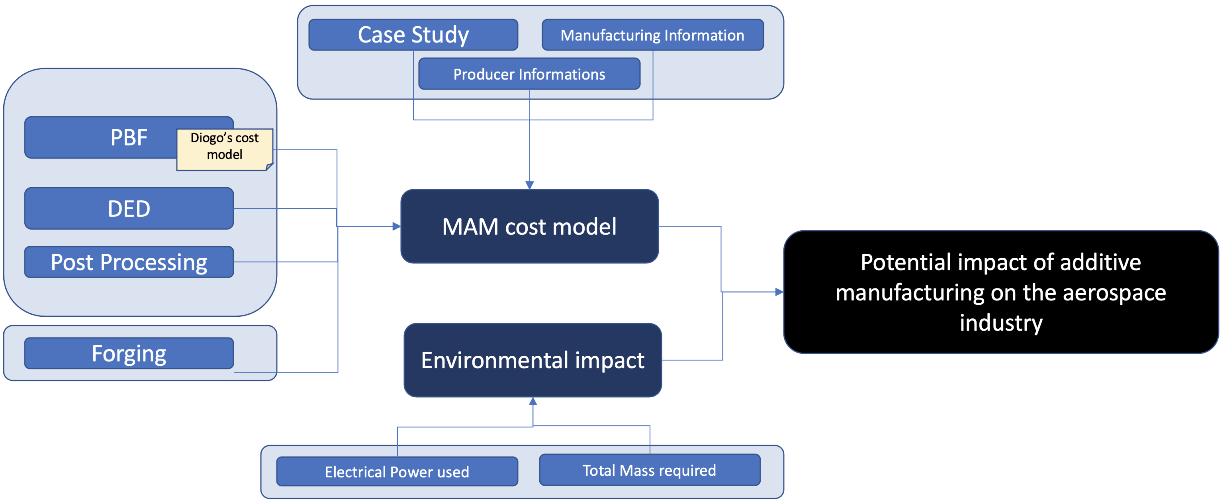


Figure 3.1: Study Scope

3.2 Additive Manufacturing

A cost analysis of a AM process is based on four main steps: preparation of the construction, which includes CAD design and preparation of the machine, Manufacturing, main stage of part construction, finishing process, to correct part properties or dimensions and for the last one Quality control, as we can see in the figure 3.2.

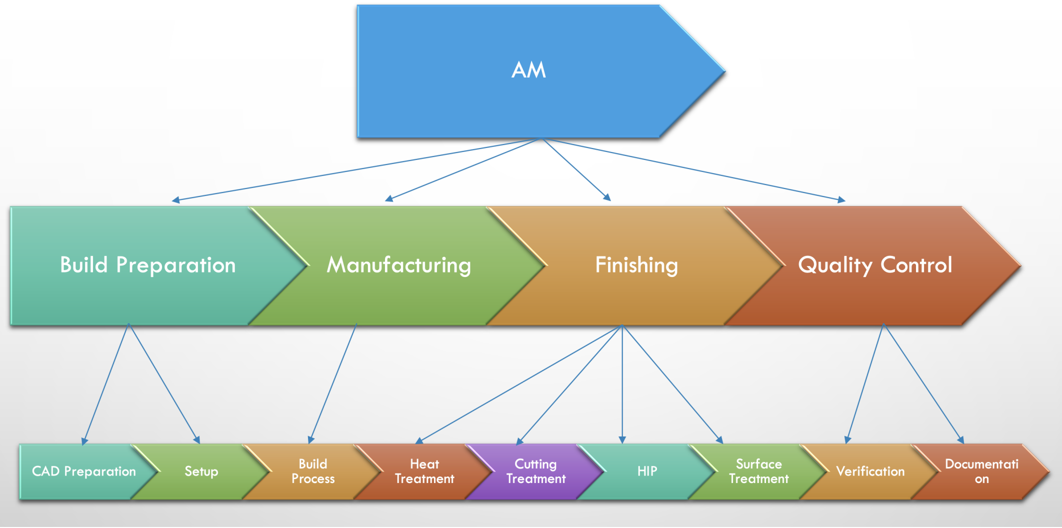


Figure 3.2: AM process Stages

3.2.1 DED Build Preparation

1. CAD Preparation

The process starts by gathering all the information about the part to build a 3D model. This model is created through a CAD Software that contains all the necessary information for the 3D printer.

Some costs are involved in this operation. A work space or desk, a computer and software licenses are required. The CAD model involves time spent by the designer which correspond to Labor Costs.

The table below summarizes the variables used in the cost model as well as the units used. All variables were estimated based on research in the national market and with companies discussion in field visits.

Table 3.1: List of required variables for CAD Preparation

Variables	***Cost Model Element***	***Value***	***Units***	***Source***
MP_DED_DP	Main Machine Price	1500	€	Companies Discussion
F_DED_DP	FootPrint	3	m2	Companies Discussion
T_DED_DP	Cycle Time of Data Preparation	5	Hour	Companies Discussion
LaborT_DED_DP	Labor Time of Data Preparation	5	Hour	Companies Discussion

2. Setup

In this step, the machine operator checks all the components of the 3D printer so that it does not compromise the construction of the part. The cost related to this step is essentially related to the time the operator spends checking and calibrating the machine. Setup time can be divided into 4:

- Holding time ($t_{holding}$) - 0.25 h -corresponds to the time required to execute the holding operation and locking the Build platform [17];
- Laser calibration time (t_{lc}) - 0.25 h - time required for the operator to calibrate the laser [17];
- Powder preparation time (t_{pp}) - 0.25 h - time needed to restore reserves of metallic powder [17];
- inert gas preparation time (t_{gp}) - 0.49 h - time required to supply gas to the chamber [17];

Then we can calculate the setup time as sum of all times presented before:

$$t_{SETUP} = t_{holding} + t_{pp} + t_{gp} + t_{lc} = 1.24h \qquad (3.1)$$

3.2.2 Build Print

3.2.2.A DED Process

This is the main stage of the DED process. The construction process is the step responsible for building the part. For this estimation the Optomec DE machine, model LENS 850R (Annex A). LENS 3D Technology by Optomec use lasers to build objects layer by layer directly from powdered metals. This process presents itself as one of the pioneering and most successful methods of DED.

This step involves several variables necessary for the construction of the cost model. Four parameters were estimated:

- Build Time;
- Gas consumption;
- Electric consumption;
- Maintenance Costs.

(i) Build Time

For DED technology is easily estimated knowing only the Deposit Rate ($deposit_{rate}$) through the specifications of the AM machine model (Inserir: Anexo Modelo da Maquina) and the mass of the part ($mass_{AM}$). Then, Buld Time of one part is obtained dividing the mass of the part by the deposit rate of the machine. To know the total Build Print time (t_{BPDED}), just multiply by the number of parts per batch (BS_{DED}), as shown in equation 3.2.

$$t_{BP/DED} = \frac{mass\_AM}{deposit\_rate} * BS_{DED} \tag{3.2}$$

(ii) Electric consumption

The electricity consumed was based on the study by Liu et al. [90]. The author, in his study makes a comparative energy analysis of AM technologies in the production of metal parts. The estimates were made by the Optomec, model LENS 750 machine, using the metal Nistelle 625, where it obtained a used energy of 1052 MJ/ kg.

The consumption of electrical energy in kWh as shwon by:

$$Electrical\_Energy\_Consumption = 1052 * K\_kWh = 292.22kWh/kg \tag{3.3}$$

Where K_kWh =0.277778 is the conversion constant from MJ to kWh. Hence, the energy used in kWh is given multiplying EEC by the mass of the part, as shwon in the equation 3.4.

$$EU\_elect_{DED} = 292.22 * mas\_AM; \tag{3.4}$$

(iii) Gas Consumption

In the same study used to estimate electricity, Liu [90] estimated gas consumption for DED machines. In his study, author refers that in DED process, powder material was delivered throught argon gas to melt pool at a considerable flow rate, typically of 10L/min.

Hence, to obtain gas consumption per hour (EU_{gas_DED}) it is only necessary to convert the value, giving a consumption of 600 L/h.

$$EU\_gas_{DED} = 600L/h \tag{3.5}$$

(iii) Maintenance Costs

The maintenance of the DED was made by a rough estimation, where it was made taking into account the percentage of maintenance of PBF in machine price.

We conclude that the maintenance price of the PBF corresponds to about 1 $\%$ of the purchase price of the machine. Thus, the DED has a maintenance of about 7000 euros per year, equation 3.6.

$$MC_{DED} = 0.01 * MP_{DED} = 7000 \tag{3.6}$$

DED Main Process Variables

Based on the 3D machine model and information gived by AM companies visited, we can define a set of necessary variables for the cost model of the DED process through the table 3.2. The table below summarizes the variables used in the cost model as well as the units used. All variables were estimated based on research in the national market and with companies discussion in field visits.

Table 3.2: Set of variables of DED process necessary for cost model

Variable	Cost Model Element	Value	Units	Source
MP_{DED}	Main Machine Price	700 000	€	LENS 850R [A]
AP_{DED}	Auxiliar Equipment Price	Given by MP_DED_{DP}	€	LENS 850R [A]
MC_{DED}	Maintenance Costs	7000 €	€	Companies Discussion
EU_gas_{DED}	Gas Usage	Given by equation 3.5	Lh	LENS 850R [A]
EU_elect_{DED}	Electricity Usage	Given by equation 3.4	kWh	Companies Discussion
BS_{DED}	Batch Size	10	Parts/batch	Companies Discussion
F_{DED}	Footprint	25.5	m2	LENS 850R [A]
T_BP_{DED}	Build Print Time	Given by equation 3.2	hours	Companies Discussion
T_SETUP_{DED}	Setup Time	Given by equation 3.1	hours	Companies Discussion
T_DP_{DED}	Data Preparation Time	5	hours	Companies Discussion
s_{DED}	Scrap Rate	30	$\%$	Estimated by [17]
r_{DED}	Reject Rate	2	$\%$	Estimated by [17]
UD_{DED}	Unplanned Downtime	2	$\%$	Companies Discussion
$LaborT_{DED}$	Labor Time	1.24	Hours	Companies Discussion

3.2.2.B PBF Process

The PBF was based on the thesis of Eng. Diogo Sequeira (2019) [6], where the model values have been converted into a script variables. Diogo developed its model based on the Renishaw AM 400 machine. The Renishaw AM 400 printer uses the SLM 3D printing technology, with a 400 W optical system providing a reduced beam diameter of 70 μm.

The system build volume is 250×250×300 mm and this MAM machine is compatible with various materials, such as aluminum, cobalt chrome, nickel, stainless steel and titanium. The only upgrade was to update the maintenance price of the equipment, based on HyperMetal. In the following table you can see a summary of the variables needed for model:

Table 3.3: Set of variables of DED process necessary for cost model

Variable	Cost Model Element	Units	Source
MP_{PBF}	Main Machine Price	€	Estimated by [6]
AP_{PBF}	Auxiliar Equipment Price	€	Company Discussion
MC_{PBF}	Maintenance Costs	€	Equipment Supplier
EU_gas_{PBF}	Gas Usage	Lh	Estimated by [6]
EU_elect_{PBF}	Electricity Usage	kWh	Estimated by [6]
BS_{PBF}	Batch Size	Parts/batch	Estimated by [6]
F_{PBF}	Footprint	m2	Estimated by [6]
T_BP_{PBF}	Build Print Time	hours	Estimated by [6]
T_SETUP_{PBF}	Setup Time	hours	Estimated by [6]
T_DP_{PBF}	Data Preparation Time	hours	Estimated by [6]
s_{PBF}	Scrap Rate	$\%$	Estimated by [6]
r_{PBF}	Reject Rate	$\%$	Estimated by [6]
UD_{PBF}	Unplanned Downtime	$\%$	Company Discussion
$LaborT_{PBF}$	Labor Time	Hours	Estimated by[6]

3.3 Forging Process

Forging always starts with the production of a die. This die is what will shape the fillet when the raw material is compressed against it.

Then we entered the stage of manufacturing the part. Here the metal is usually required to be preheated. This preheating can be at a higher temperature (hot forging) or at a lower temperature (warm forging). The cold forging option was not considered, since in the aerospace industry it works with very hard materials, such as titanium, and it is always necessary to soften it to make it more malleable and less brittle able to withstand the great pressures of the forging process..

After preheating the metal is pressed against the die. There are several types of machines and in this model three types have been integrated: pneumatic hammer, hydraulic press and screw press.

After the piece takes shape, some type of post treatment may be necessary to correct dimensions or refine some more physical characteristics. Included in this model are heat treatment, two surface treatments, the grinder and a thermochemical, and two cutting treatments, Electrical Discharge Machining (EDM) and MultiAxis Mills (MM).

The last step is to verify that the part meets all the requirements established initially and to deal with a series of documentation that the aerospace sector requires.

The figure 3.3 shows a proposal for a set of substages for a typical production line of a forged part which can be edit.

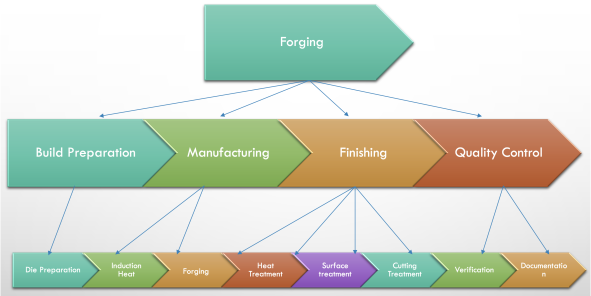


Figure 3.3: Forging Stages and Substages

3.3.1 Build Preparation

1. Die Preparation

At the beginning of the process, the data for the part must be prepared. Since forging is an Injection Molding Presses technique, it is always necessary to design a die. To create a die, several steps are necessary, depending on a number of diferents factors. After contact with a forging operator, an range price range of production cost was established. Where the die manufacturing (C_{DM}) was based in rough company estimation between 4000-8000€ depending of the complexity of the part, .

Another important data is the number of parts that a die can build (N_{DIE}), a die after N manufactured parts begins to wear out, losing quality and compromising the quality of the process, requiring replacement. All the information was gived by **forged!** (**forged!**) companies visited.

Knowing that these values vary depending on the complexity of the piece, an escalation of complexity (F) 1-3 was created, 1 being a very simple piece and 3 a more complex piece. This scale corresponds to a 33% price variation.

The total cost of this activity is given by the equation 3.7.

$$C_{Die} = (C_{DM}) * (1 - F) * |\frac{APV}{N_{DIE}}| \tag{3.7}$$

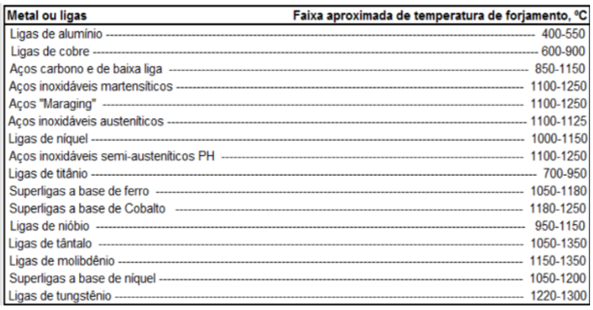
Table 3.4: Set of Variables of Die Manufacturing Step Required for Cost Model

Variable	Cost Model Element	Value	Units	Source
C_{DM}	Cost of Die Manufacturing	6000	€/Part	Companies Discussion
N_{Die}	Number of Part that it can produce	150	Parts	Companies Discussion
F	Complexity Part Factor	[1-3]	-	Companies Discussion
C_{Die}	Cost of Die	Given By Equation 3.7	€/Part	Equation 3.7

3.3.2 Manufacturing

1. Pre Heating

This stage depends of the type of forging, hot or cold/warm. The user is allowed to choose between hot forging and cold forging. For the last one, it is considered that there is always a small heating, once that the aerospace industry works with hard metals that need at least a warm forging before being subjected to high pressures, as said before.



Metal ou ligas	Faixa aproximada de temperatura de forjamento, °C
Ligas de alumínio	400-550
Ligas de cobre	600-900
Aços carbono e de baixa liga	850-1150
Aços inoxidáveis martensíticos	1100-1250
Aços "Maraging"	1100-1250
Aços inoxidáveis austeníticos	1100-1125
Ligas de níquel	1000-1150
Aços inoxidáveis semi-austeníticos PH	1100-1250
Ligas de titânio	700-950
Superligas a base de ferro	1050-1180
Superligas a base de Cobalto	1180-1250
Ligas de nióbio	950-1150
Ligas de tântalo	1050-1350
Ligas de molibdênio	1150-1350
Superligas a base de níquel	1050-1200
Ligas de tungstênio	1220-1300

Figure 3.4: Preheating Hot Forging tempertures

Source: Estudo Comparativo Para Fabricação de Peças Aeronauticas: Forjamento X Usinagem [52]

The figure 3.4 shows the heating temperature in hot forging for various metals e alloys. Knowing that this temperature is about 60% and that in cold forging it can reach 30% of the fusion point temperature [52], it is easy to estimate knowing the type of forging and the metal at which temperature to be heated. Knowing also that the preheating has a time between 10-20min [56], with 10min corresponding to metals with lower melting points and 20min with higher melting points and create a linear fuction, to estimate cicle time of preheat ($t_{cycle_{PH}}$), between the forging temperature and the preheating cycle time, equation 3.8.

$$t_{cycle_{PH}} = temp_{preheat} = (\frac{1}{95} * RM_{temp_{forging}} + \frac{550}{95}) * \frac{1}{60} \tag{3.8}$$

The specifications of the equipment in appendix [A], the maximum batch comes in kilograms and it is necessary to divid by the mass of the part ($mass\_forging$) to have the number of parts per lot ($BS_{preHeat}$), as the following equation:

$$BS_{PH} = \frac{27.2}{mass\_forging} \tag{3.9}$$

After researching the furnace models, interviewing machine operators and searching the literature, the variables estimated are present in the table 3.5.

Table 3.5: Set of variables of PreHeat Step Required for Cost Model

Variable	Cost Model Element	Value	Units	Sources
MP_{PH}	Main Machine Price	100 000	€	Estimated by [80]
AP_{PH}	Auxiliar Equipment Price	10 000	€	Estimated by [80]
MC_{PH}	Maintenance Costs	10 000	€	Estimated by [80]
EU_gas_{PH}	Gas Usage	453	L/h	GH IA Model VF-35 [A]
EU_elect_{PH}	Electricity Usage	17	kWh	GH IA Model VF-35 [A]
BS_{PH}	Batch Size	Given by Equation 3.9	Parts/batch	GH IA Model VF-35 [A]
F_{PH}	Footprint	17.787 [1]	m2	GH IA Model VF-35 [A]
$T\_loadunload_{PH}$	Load+ unload Time	0.25	hours	Companies Discussions
T_cycle_{PH}	Cycle Time	Given by Equation 3.8	hours	Estimated by [80]
s_{PH}	Scrap Rate	0	$\%$	Estimated by [80]
r_{PH}	Reject Rate	1	$\%$	Estimated by [80]
UD_{PH}	Unplanned Downtime	2	$\%$	Estimated by [80]
$LaborT_{PH}$	Labor Time	0.25	Hours	Companies Discussions

2. Forging

This substage is when the metal bars take on the shape of the required part. For this, three types of machines can be used: hydraulic press, screw press or pneumatic hammer. In this model the user is allowed to select which type of machine is needed.

For each type of machine, a set of variables was estimated based on existing models, Machine Price (MP_i), Electricity Consumption (EU_elect_i) and Footprint (F_i), as we can see in the table 3.6.

Table 3.6: Set of specifications for Forging Hammer, Screw Press and Hydraulic Press

Variable	Hydralic Press	Screw Press	Forging Hammer	Units
MP_i	6000	55900	158000	€
F_i	16.375	19.697	23.4	m2
EU_elect_i	132	22	60	kWh
Machine Model	Schuler GLF 1800V [A]	MEC J53 [A]	YHA 3-1500T [A]	-

After interviewing forging operators and searching in the literature, a set of variables in the table 3.7 was estimated.

3.4 Finishing Processes

3.4.1 Heat Treatment

In Heat Treatment, operators place the metal object in an oven, heating a part to a certain temperature and then it is cooled in a controlled manner depending on the type of treatment selected.

Table 3.7: Set of Variables of Forging Step Required for Cost Model

Variable	Cost Model Element	Value	Units	Sources
$MP_{forging}$	Main Machine Price	Table 3.6	€	Equipment Supplier
$AP_{forging}$	Auxiliar Equipment Price	5% of MP_i	€	Estimated by [80]
$MC_{forging}$	Maintenance Costs	5% of MP_i	€	Estimated by [80]
$FP_{forging}$	Fixture/Tooling Price	Given By Eq. 3.7	€	Companies Discussions
$EU\_gas_{forging}$	Gas Usage	0	Lh	GLO 120/11-1G [A]
$EU\_elect_{forging}$	Electricity Usage	Table 3.6	kWh	GLO 120/11-1G [A]
$BS_{forging}$	Batch Size	1	Parts/batch	GLO 120/11-1G [A]
$F_{forging}$	Footprint	Table 3.6	m2	GLO 120/11-1G [A]
$T\_loadunload_{forging}$	Load + unload Time	$\frac{5}{3600}$	Hours	Companies Discussions
$T\_cycle_{forging}$	Cycle Time	$\frac{1}{500}$	Hours	Estimated by [80]
$s_{forging}$	Scrap Rate	30	$\%$	Estimated by [80]
$r_{forging}$	Reject Rate	2	$\%$	Estimated by [80]
$UD_{forging}$	Unplanned Downtime	2	$\%$	Estimated by [80]
$LaborT_{forging}$	Labor Time	$\frac{5}{3600}$	Hours	Companies Discussions

Four types of heat treatment most used can be chosen as post processing in this model: Annealing, Quenching, Tempering and Normalization. For each heat treatment there are different preheating times, soak time and cooling time, for each type of heat treatment .

Based on the book Heat Treatment [56], it is reasonable to estimate some values in the table below.

Table 3.8: Set of estimated value for each type of Heat Treatment

	Annealing	***Quenching***	***Tempering***	***Normalization***
PreHeat	10-15min	10min	10min	10-15min
Soak Time	1h/25mm Thickness	2h/25min of Thickness	2h/25min of Thickness	20min
Cooling Time	25 h	0	0	15min

The cycle times of the heat treatment is estimated based on the table 3.8. Another set of variables is needed for the cost model, after selecting a furnace model, interviewed forging operators and searching on the literature, the variables in the table 3.9 were estimated.

Table 3.9: Set of variables of Heat Treatment step necessaries for cost model

Variable	Cost Model Element	Value	Units	Sources
MP_{HT}	Main Machine Price	50 000	€	Estimated by [80]
AP_{HT}	Auxiliar Equipment Price	0	€	Company Discussion
MC_{HT}	Maintenance Costs	5% of MP$_{HT}$	€	Estimated by [80]
EU_gas_{HT}	Gas Usage	200	Lh	Model GLO 40/11-1G [A]
EU_elect_{HT}	Electricity Usage	25	kWh	Model GLO 40/11-1G [A]
BS_{HT}	Batch Size	$\frac{20}{mass\_forging}$	Parts/batch	Estimated by [80]
F_{HT}	Footprint	17.52	m2	Model GLO 40/11-1G [A]
$T\_loadunload_{HT}$	Load+ unload Time	0.25	hours	Companies Discussions
T_cycle_{HT}	Cycle Time	Table 3.8	hours	Estimated by [80]
s_{HT}	Scrap Rate	0	$\%$	Estimated by [80]
r_{HT}	Reject Rate	2	$\%$	Estimated by [80]
UD_{HT}	Unplanned Downtime	2	$\%$	Estimated by [80]
$LaborT_{HT}$	Labor Time	0.25	Hours	Companies Discussions

3.4.2 Surface Treatments

Surface treatment is usually necessary after forging or Build Print process. In this model, three types are proposed: grinder, thermo-chemical treatment and shot peening.

A. Grinder

An estimate of the cycle time was made through a linear regression between the surface area and the cycle time of the machine in this step.

To calculate the surface area of the part, a cube was considered. For example, a screw with 4cm in diameter and 10cm in length, according to this estimate, had a surface area equivalent to a cobblestone with 4x4x10 cm, figure 3.5.

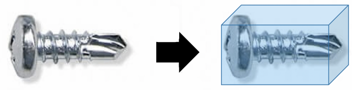


Figure 3.5: Preheating Hot Forging tempertures

On a field visit to a reference company of forging manufacturing. An experiment was done to estimate the cycle time of the grinding process. The experiment was then carried out in which the cycle time of a given 4 piece was taken, repeating the procedure for 3 more distinct pieces and the average was calculated, table 3.10. Thus, it was possible to perform a linear regression to estimate the cycle time of the grinder for all parts.

Further estimates were needed. The table 3.11 shows the input variables as well as the source from which these estimates were made.

Table 3.10: Data of Grinder experience

	Part 1	*Part 2*	*Part 3*	*Part 4*
Timing	1 [min]	5 [min]	40 [min]	60 [min]
Surface Area	6 [mm2]	3.375 [mm2]	0.5 [m2]	1 [m2]

After choosing the model of the grinder machine, interviewed Grinder operators in a field visit and researched on the literature, the set of variables was put together on the table 3.11.

B. Thermochemical Surface Treatment

Thermochemical treatment can be applied right after the heat treatment. It consists of placing the piece in a carbon-rich environment to hard the surface of the part. The cycle time (T_cycle_{TT}) were estimated according to the table 3.12 based on the book [52]:

It should be noted that the PreHeat of the thermochemical treatment was considered zero, since the Thermochemical Treatment is done after the Heat Treatment, not requiring a new preheating. For the soak time, the average of the range estimated in the literature was considered. The cooling time is considered zero because after removed the part from the furnace, it is cooled in the open air.

After researching furnace models, interviewing workers in a field visit and researching the literature, the variables present in the table 3.13 were estimated.

H

Table 3.11: Set of variables of Grinder step necessary for cost model

Variable	Cost Model Element	Value	Units	Sources
MP_G	Main Machine Price	100 000	€	CNC Model s500x [A]
AP_G	Auxiliar Equipment Price	0	€	Companies Discussions
MC_G	Maintenance Costs	5% of Machine Price	€	Companies Discussions
EU_gas_G	Gas Usage	0	Lh	CNC Model s500x [A]
EU_elect_G	Electricity Usage	16	kWh	CNC Model s500x [A]
BS_G	Batch Size	1	Parts/batch	CNC Model s500x [A]
F_G	Footprint	18.96	m2	CNC Model s500x [A]
$T\_loadunload_G$	Load + unload Time	0.02	Hours	Companies Discussions
T_cycle_G	Cycle Time	Estimated by L. R.	hours	Companies Discussions
s_G	Scrap Rate	5	%	Estimated by [80]
r_G	Reject Rate	5	%	Estimated by [80]
UD_G	Unplanned Downtime	2	%	Estimated by [80]
$LaborT_G$	Labor Time	0.02	Hours	Companies Discussions

Table 3.12: Cycle time of Thermochemical Surface Treatment

	Pre Heat	*Soak Time*	*Cooling Time*
TermoChemical Treat.	0	4-12h	Open air

C. Shot Peening

Shot Peening consists of reaching the surface of the part with round projectiles, such as glass or ceramic, creating a plastic deformation producing a layer of compressive residual stress.

After choosing the model of the shot peening machine, information gived by HyperMetal and researched on the literature [80], the set of variables was put together on the table 3.4.2.

Variable	Cost Model Element	Value	Units	Source
MP_{SP}	Main Machine Price	9990	€	Estimated by [80]
AP_{SP}	Auxiliar Equipment Price	10% Machine Price	€	Estimated by [80]
MC_{SP}	Maintenance Costs	4995	€	Estimated by [80]
EU_gas_{SP}	Gas Usage	0	Lh	Estimated by [80]
EU_elect_{SP}	Electricity Usage	0.2	kWh	Estimated by [80]
BS_{SP}	Batch Size	1	parts/batch	Estimated by [80]
F_{SP}	Footprint	18.1	m2	Estimated by [80]
T_cycle_{SP}	Cycle Time	0.5	hours	Estimated by [80]
$T\_loadunload_{SP}$	Load Unload Time	0.25	hours	Estimated by [80]
s_{SP}	Scrap Rate	2	%	Estimated by [80]
r_{SP}	Reject Rate	1	%	Estimated by [80]
UD_{SP}	Unplanned Downtime	2	%	Estimated by [80]
$LaborT_{SP}$	Labor Time	0.25	Hours	Estimated by [80]

3.4.3 Cutting Treatments

A. MultiAxis Mills

The MM process is a cutting tool that moves in different directions depending on the model of the machine. This post-processing is used to correct dimensions or give more detail to the piece, so it is difficult to estimate the cycle time, since it depends on what the producer or designer designed the

Table 3.13: Set of variables of Thermochemical Treatment step necessary for cost model

Variable	Cost Model Element	Value	Units	Source
MP_{TT}	Main Machine Price	50 000	€	Estimated by [80]
AP_{TT}	Auxiliar Equipment Price	1000	€	Companie Discussion
MC_{TT}	Maintenance Costs	5% MP$_{TT}$	€	Estimated by [80]
EU_gas_{TT}	Gas Usage	200	Lh	Model GLO 40/11-1G [A]
EU_elect_{TT}	Electricity Usage	25	kWh	Model GLO 40/11-1G [A]
BS_{TT}	Batch Size	$\frac{20}{mass_forging}$	Parts/batch	Model GLO 40/11-1G [A]
F_{TT}	Footprint	17.52	m2	Model GLO 40/11-1G [A]
$T\_loadunload_{TT}$	Load+ unload Time	0.25	Hours	Companies Discussions
T_cycle_{TT}	Cycle Time	8	Hours	Estimated by [80]
s_{TT}	Scrap Rate	0	%	Estimated by [80]
r_{TT}	Reject Rate	2	%	Estimated by [80]
UD_{TT}	Unplanned Downtime	2	%	Estimated by [80]
$LaborT_{TT}$	Labor Time	0.25	Hours	Companies Discussions

piece. For that, the complexity factor (F) with a variation of 20% was used and an estimate of cycle time (t_cycle_{MM}) made by Prof Jaime [80]. This basic estimate was made according to the equation:

$$t\_cycle_{MM} = t_{cycle_M M} * (1 - F) \tag{3.10}$$

For the costs of this step, it was necessary to know more variables that were estimated by interviews in a metal manufacturing company, research of machine models and by literature [80]. The table 3.14 shows the variables and the source from which they were estimated.

Table 3.14: Set of variables of MultiAxis Mills step necessary for cost model

Variable	Cost Model Element	Value	Units	Source
MP_{MM}	Main Machine Price	399950	€	Estimated by [80]
AP_{MM}	Auxiliar Equipment Price	0	€	Estimated by [80]
MC_{MM}	Maintenance Costs	22997	€	Estimated by [80]
EU_gas_{MM}	Gas Usage	0	Lh	Estimated by [80]
EU_elect_{MM}	Electricity Usage	18	kWh	Estimated by [80]
BS_{MM}	Batch Size	$\frac{2}{mass\_forging}$	Parts/batch	Estimated by [80]
F_{MM}	Footprint	19	m2	Estimated by [80]
$T\_loadunload_{MM}$	Load+ unload Time	0.25	hours	Companies Discussion
T_cycle_{MM}	Cycle Time	Given by eq. 3.10	hours	Author Estimation
s_{MM}	Scrap Rate	10	%	Estimated by [80]
r_{MM}	Reject Rate	2	%	Estimated by [80]
UD_{MM}	Unplanned Downtime	2	%	Estimated by [80]
$LaborT_{MM}$	Labor Time	0.25	Hours	Companies Discussions

B. Wire EDM

Wire EDM is on par with MultiAxis Mills a cutting tool. This again makes it difficult to estimate the cycle time. The complexity factor (F) of the part was used that would make the cycle time ($t_{cycle_E DM}$) that Jaime's estimated in his model [80].

$$t\_cycle_{EDM} = t\_cycle_{EDM} * (1 - F) \tag{3.11}$$

The remaining variables in table 3.15 required were estimated by interviews in a metal manufacturing company, research of machine models and by literature [80].

Table 3.15: Set of variables of EDM step necessary for cost model

Variable	Cost Model Element	Value	Units	Source
MP_{EDM}	Main Machine Price	91581	€	Mitsubishi MV1200R [A]
AP_{EDM}	Auxiliar Equipment Price	0	€	Mitsubishi MV1200R [A]
MC_{EDM}	Maintenance Costs	5% of MP$_{EDM}$	€	Companies Discussions
EU_gas_{EDM}	Gas Usage	0	Lh	Mitsubishi MV1200R [A]
EU_elect_{EDM}	Electricity Usage	56.08	kWh	Mitsubishi MV1200R [A]
BS_{EDM}	Batch Size	$\frac{6}{mass\_part}$	Parts/batch	Mitsubishi MV1200R [A]
F_{EDM}	Footprint	20.589	m2	Mitsubishi MV1200R [A]
$T\_loadunload_{EDM}$	Load+ unload Time	0.25	Hours	Companies Discussions
T_cycle_{EDM}	Cycle Time	Given by eq. 3.11	Hours	Companies Discussion
s_{EDM}	Scrap Rate	5	%	Estimated by [80]
r_{EDM}	Reject Rate	2	%	Estimated by [80]
UD_{EDM}	Unplanned Downtime	2	%	Estimated by [80]
$LaborT_{EDM}$	Labor Time	0.25	Hours	Companies Discussions

3.4.4 Hot Isostatic Pressing

Hot Isostatic Pressing (HIP) is a post-processing that reduces casting defects and allows the elimination of pores, increasing the useful life of the part.

HIP subjects the part to compression with a high temperature and isostatic gas pressure at the same time. The table 3.16 shows the necessary variables based in literature review **??** and interviews in a metal manufacturing company.

Table 3.16: Set of variables of HIP step necessary for cost model

Variable	Cost Model Element	Value	Units	Source
MP_{HIP}	Main Machine Price	2 500 000	€	Estimated by [80]
AP_{HIP}	Auxiliar Equipment Price	0	€	Estimated by [91]
MC_{HIP}	Maintenance Costs	2% Machine Price	€	Estimated by [80]
EU_gas_{HIP}	Gas Usage	6	Nm^3	Estimated by [91]
EU_elect_{HIP}	Electricity Usage	128	kWh	Estimated by [91]
BS_{HIP}	Batch Size	$\frac{34}{mass\_AM}$	Parts/batch	Estimated by [91]
F_{HIP}	Footprint	16.394	m2	Estimated by [91]
T_cycle_{HIP}	Cycle Time	7.6	Hours	Estimated by [91]
$T\_loadunload_{HIP}$	Load and Unload Time	1.1	Hours	Estimated by [91]
s_{HIP}	Scrap Rate	2	%	Estimated by [80]
r_{HIP}	Reject Rate	2	%	Estimated by [80]
UD_{HIP}	Unplanned Downtime	2	%	Estimated by [80]
$LaborT_{HIP}$	Labor Time	1.1	Hours	Companies Discussion

3.4.5 Verification and Validation

After any part is built, it is necessary to check and document it. This is the final stage of the whole process, which involves qualifying and measuring the dimensions of the piece to find out if it meets the geometric requirements and design tolerances.

To check the dimensioning requirements, it used a Coordinate Measuring Machine (CMM), figure 3.6.

The variables used to calculate the cost of verification and validation are shown in the table 3.17.

Figure 3.6: Coordinate Measuring Machine CRYSTA-Apex S 9106 developed by the Japanese company Mitutoyo

Table 3.17: Set of variables of CMM step necessary for cost model

Variables	Cost Model Element	Value	Units	Source
MP_QC	Machine Price	20 000	€	Estimated by [17]
MC_QC	Maintenance Costs	5% Machine Price	€	Estimated by [17]
F_QC	FootPrint	18	m2	Estimated by [17]
T_cycle_QC	Cycle Time	0.5	Hour	Estimated by [17]
$T\_loadunload\_QC$	Cycle Time	0.167	Hour	Estimated by [17]
$LaborT\_QC$	Labor Time	0.167	Hour	Estimated by [17]
EU_QC	Electric consumption	4	kWh	Estimated by [17]

3.5 Decision Rules Equations

After gathering all the information for each stage of the processes, equations and decision rules are used to calculate the cost of manufacturing the part for each technology. First of all, it is necessary to know a set of inputs associated with the part and company, present in the table **??**, which allow with script variables calculating costs for each stage of the process and later the total costs of build a piece.

3.5.1 Initial Inputs

Any cost model needs a set of information to be able to calculate the cost of a part. In this model the inputs are divided into 3 categories:

- Producer information, as shown in table 3.18;
- Part information, as shown in table 3.19;
- Manufacturing Information, as shown in table 3.20.

Table 3.18: Producer Inputs

Variable	Cost Model Element	Units
DPY	Working Days/Year	days/yr
NS	No Shifts	hr/Days
UB	Unpaid Breaks	hr/Day
PB	Paid Breaks	hr/Day
UD	Unplanned Downtime	hr/Day
sh	Salary Per Hour	€/h
p_e	Price of Electricity	€/Kwh
p_b	Price of Building	$/m^3$
p_g	Price of Gas	€/m^3
p_s	Price of Scrap	€/kg
p_{RM}	Price of Raw Material	€/kg
r	Interest Rate	%

Table 3.19: Part Inputs

Variable	**Cost Model** Element	Units
volume	Part Volume	mm^3
$Mass_i$	Part Mass	kg
Max_height_part	Maximum Part Height	mm
Max_width_part	Maximum Part Width	mm
Max_lenght_part	Maximum Part Length	mm
thickness	Minimum Thickness of Part	mm
F	Part Complexity Factor	Units

Table 3.20: Manufacturing Inputs

Variable	**Cost Model** Element	Units
APV	Number of Good Per Year	Units/Year
RM	Raw Material	-
forging_1	Hot or Cold Forging Selection	-
forging_2	Forging Machines Selection	-
HT	Heat Treatments Selection	-
forging_FT	Forging Finishing Treatments	-
AM_FT	AM Finishing Treatments	-

3.5.2 Time Definitions

To proceed with the production calculations it is useful to define some time variables which facilitate the calculation of costs in the model.:

- *Line Time Available* (LTA_i) - time available over the year at production step i, for the production of parts. In our model, Available Line Time was calculated as follows:

$$LTA_i = DPY(24 - NS - UB - PB - UD) \tag{3.12}$$

- *Effective Volume Production* ($effPV_i$)- the number of parts needed to produce throughout the year to achieve the desired "good" parts (APV). As we can see in the equation 3.13, the effective production volume ($effPV_i$) is calculated as the effective production volume of the next stage ($effPV_{i+1}$), in the production line, divided for the rejection rate for that stage(r_i). It should be noted that the effetive production volume of the penultimate stage is determined by the number of good parts to be produced during a year (APV) divided by the rejection rate of that same stage(r_i).

$$effPV_i = \frac{effPV_{i+1}}{(1 - r_i)} \tag{3.13}$$

- *Required Line Time* ($reqLTi$) - Time required throughout the year to produce Effective Volume Production. For forging and post-processing, the required line time ($reqLT_i$) is calculated using the equation 3.14. Here the cycle time (T_cycle_i) is the time a batch is built and the load and unload time

($T\_loadunload_i$) is the time to load and unload the machine. The batch size (BS_i) is the number of pieces that are produced together.

$$reqLT_i = \frac{effPV_i * (T\_cycle_i + T\_loadunload_i)}{BS_i} \tag{3.14}$$

For the case of additive manufacturing, the cycle time and load and unload time are replaced by the build print time and the machine setup time,as we can see in the equation 3.15.

$$reqLT_i = \frac{effPV_i * (T\_BP_i + T\_SETUP_i)}{BS_i} \tag{3.15}$$

- Lines Required (LR_i) - Number of stations required to reach the Effective volume yield per stage. The required lines are calculated as parallel production. To achieve the number of good parts per year, sometimes it is necessary to have more machines running at the same time. The machines are added to the mill line and several machines are performing the same task. The calculation of the required lines, assuming parallel production, can be seen in the equation 3.16.

$$LR_i = \frac{reqLT_i}{LTA - (DPY * UD_i)} \tag{3.16}$$

3.5.3 Scripts to Costs

After we have all the necessary inputs and variables for all processes, it is possible to calculate the production costs. These costs correspond to the sum of all the money spent on the production of the piece directly or indirectly. The Total production costs are given by the following equation:

$$Total\_costs = Variable\_Costs + Fixed\_Costs; \tag{3.17}$$

The variable costs ($Variable\_Costs$) are the costs vary proportionally with the volume of production, as material costs, electricity and gas costs and Labor Costs. While fixed costs ($Fixed\_Costs$) correspond to costs that do not vary in value with the volume of production, as maintenance costs, Building costs and capital invested.

A. Variables Costs

1) Material Usage

Raw Material per Part

Knowing the mass of part after a main build process ($mass\_forging$ or $mass\_AM$,) it is needful to know the raw material required in the first stage of the process (RM_used), that is, before preheating in the case of forging 3.18 and before Build print in the case of AM technologies 3.19. This raw material has to take into account the scrap rate (s_i) that remains in the process and the mass of the part (it is considered after the manufacturing stage, after forging ($mass_forging$) or after Build Print ($mass_AM$) in AM technologies), as we can see in the equations bellow:

$$RM\_used = mass\_forging * (1 + s_{forging}) * (1 + s_{preheating}) \tag{3.18}$$

$$RM\_used = mass\_AM * (1 + s_{DED})) \tag{3.19}$$

Mass Requerired per Step

Then the mass required before is step i is calculated as the Raw Material per Part (RM_used) minus the scrap loss from all previous processes (s_i):

$$mass\_req_i = RM\_used * \prod(1 - s_n) \tag{3.20}$$

where i is the process step and n the previous steps ($n < i$).

Mass Usage left in the Stage

So, it is now possible to calculate the annual scrap mass (U_mass_i) left at each stage. This calculation is done by subtracting the mass required before step i ($mass\_req_i$) minus the mass required after process ($mass\_req_{i+1}$) for all parts manufactured annually in that step i ($effPV_i$):

$$U\_mass_i = (mass\_req_i - mass\_req_{i+1}) * effPV_i \tag{3.21}$$

Number of Bad Parts per Stage

Now it is necessary to calculate the number of rejected parts ($Nr\_bad\_parts_i$) left in each process, subtracting the volume of parts produced in step i ($effPV_i$) by the next step ($effPV_{i+1}$):

$$Nr\_bad\_parts_i = effPV_i - effPV_{i+1} \tag{3.22}$$

Total Mass Left in the stage

The total mass that remains in each step of the process is the sum of the scrap U_mass_i and the mass of the number of pieces rejected in step i:

$$Total\_mass_i = U\_mass_i + Nr\_bad\_parts_i * mass\_req_i \tag{3.23}$$

Note: The good part mass was added to the part construction stage, in the forging in the traditional method and in the build print in the AM technologies.

Anual Material Costs in each Step

Then Annual Material Costs in each step i is the multiplication of the total mass rejected $Total\_mass_i$ in each step i by the price of the raw material RM_price.

$$MaterialCost_i = RM\_price * Total\_mass_i; \tag{3.24}$$

2) Sold Scrapt

The material left over in each process, called scrap, can be resold. This resale will result in a decrease in variable costs. So, the material sold is the total rejected mass ($Total\_mass$) multiplied by the scrap resale price p_s:

$$MaterialSold_i = Total\_mass_i * p_s; \tag{3.25}$$

For the pre-heating, Heat Treatment and Hot Isostatic pressing processes, the scrap sold is considered zero. Once that the loss of mass in these processes is due to the atomic rearrangement and not to the scrap left by the process.

3) Labor Usage

Annual Paid Time

The annual time paid (APT_i) is the work hours per year of the worker in process i:

$$APT_i = LaborT_i * |\frac{effPV_i}{BS_i}| \tag{3.26}$$

Where ($LaborT_i$) is the number of hours the worker needs to spend in process i per batch, ($effPV_i$) is the number of part produced good and bad over a year and (BS_i) is the number of parts produced in the same group.

Annual Labor Cost

The annual labor cost per process step is calculated according to:

$$ALC_i = APT_i * sh \tag{3.27}$$

Where sh is the salary paid per hour.

4) Energy Usage

Annual Energy Usage

The calculation of energy used per batch (EU_elect_i) is based on the energy consumed per hour (EU_elect_i) of the machines in step i of production and the total time required $reqLT_i$ in step i to produce the total number of good parts required. The equation calculates the annual energy used per stage i AEU_i for each stage of the process for one year:

$$AEU\_elect_i = EU_i * reqLT_i; \tag{3.28}$$

Annual Energy Cost

To calculate the annual cost of energy AEC_i consumed by step i, multiply the annual energy used AEU_elect_i by the price of electricity p_e:

$$AEC_i = AEU\_elect_i * p_e \tag{3.29}$$

5) Gas Usage

Annual Gas Usage

For the calculation of the annual gas used per batch GAU_i it is based on volume per hour of gas used EU_gas_i by the machines used in that production step i multiplied by the time necessary to produce the number of good parts per step i $reqLT_i$:

$$GAU_i = EU\_gas_i * reqLT_i \tag{3.30}$$

Annual Gas Cost

To calculate the annual gas costs in step iAGC_i, the gas price $p_g$is multiplied by the annual gas consumption AGC_i:

$$AGC_i = GAU_i * p_g; \tag{3.31}$$

B. Fixed Costs

1) Capital Costs

Capital Invested

The calculation of the cost of capital begins with the calculation of the invested capital C_i as the cost of purchasing the main machine MP_i and auxiliary equipmentAP_i:

$$C_i = (MP_i + AP_i) \tag{3.32}$$

Amortized Costs

Capital costs take into account the value of money over time. For this purpose, the flow of N constant payments, R, equivalent to the current sum C, where C is the capital price and N is the number of years during which the purchase is amortized and r is the discount rate, is calculated. Thus the calculation of the flow of constant payments comes:

$$AR_i = C_i * R; \tag{3.33}$$

$$R = \frac{(1+r)^N * r}{(1+r)^N - 1} \tag{3.34}$$

Annual Capital Costs

The annual cost of capital is calculated using the R multiplied by Lines required:

$$ACapital_i = \frac{AR_i * |LR_i|}{LTA_i} * reqLT_i; \tag{3.35}$$

2) Building Costs

Annual Building Costs

The annual cost of the building per step i is calculated through the building space required F_i per production step multiplied by the number of Lines required LR_i and the price of the building per m2 (p_b), amortized R:

$$BU_i = F_i * |LR_i| * p_b * R \tag{3.36}$$

The annual building Costs per stage i $ABuildingC_i$ of production is calculated by the reason of Building Used BU_i and the total time available for production LTA_i. This ratio will be a cost per hour, which is multiplied by the amount of time required per step i $reqLT_i$ of production to achieve the desired number of good parts.

$$ABuildingC_i = \frac{BU_i}{LTA_i} * reqLT_i \tag{3.37}$$

3) Maintenance Costs

The annual maintenance cost per step i AMC_i is calculated using the average maintenance cost of each machine in step i MC_i multiplied by the number of required lines used in step i LR_i:

$$AMC_i = MC_i * LR_i \tag{3.38}$$

4

Results and Discussion

This chapter presents a case study used for our model as well as an analysis of the costs obtained. An estimation is made for the selected part with the three technologies of our model and a comparisonof their estimated costs, along with an analysis of the post-processing. Finally, a discussion about theenvironmental impact was made for each technologies.

4.1 Case Study Selected

4.1.1 Part Selected

The part illustrated in figure 4.1 is a bracket and it is a representative part of the aerospace industry. The part's choice was based on its size and shape complexity, but also because it has been optimized for additive manufacturing, figure 4.2 and 4.3.

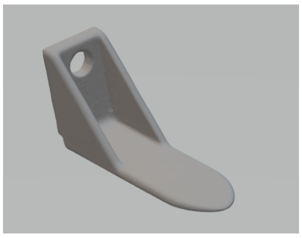


Figure 4.1: Case Study Original Part

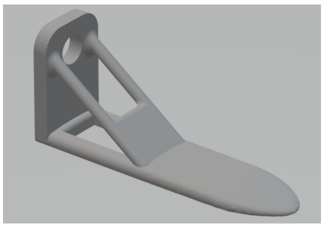


Figure 4.2: First possibility for a part optimization

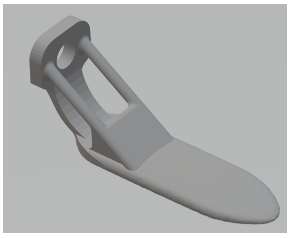


Figure 4.3: Second possibility for a part optimization

Source: Metal Additive Manufacturing in Aeronautics: a Life Cycle Cost Perspective [6]

Taking advantage of the free geometry offered by AM, Topological Optimization (TO) is used normally. TO offers an improvement in the distribution of material for a given order. The main objective is to reduce weight without compromising the original strength of the piece produced by a traditional method. Figures 4.2 and 4.3 show two optimization possibilities for the conventionally manufactured part previously presented, which allowed a weight reduction of 36% is achieved.

The table 4.1 presents a set of variables of the case study part needed as input in this model.

Table 4.1: Production Data of the Part

Variable	Cost Model Element	Value	Units
$mass_{forging}$	Original Mass	0.444	hours
$mass_{AM}$	Optimized Mass	0.285	hours
Max_height_Part	Max Height	135.1	mm
Max_width_Part	Max Width	35	mm
Max_length_Part	Max Length	93.34	mm
volume	Original Volume	35151.1	mm3
thickness	Thickness	10	mm
RM_type	Raw Material	Tool Steel M300	-
F	Complexity of the Part	2	-

4.1.2 Producer Informations

The cost model has a some variables that depend on the information of the producer that can change depending of the company and of the country. For this case study, the necessary data were estimated based on reasonable values validated by Hypermetal and other companies in the same area. The producer variables are presented in table 4.2.

Table 4.2: Producer Variables

Variable	Cost Model Element	Value	Units	Source
RM_price(1)	Material Price Forging	3	€/kg	Equipment Supplier
RM_price(2)	Material Price PBF	25	€/kg	Equipment Supplier
RM_price(3)	Material Price DED	30	€/kg	Equipment Supplier
p_s	Scrap Sold Price	0.1	€/kg	Equipment Supplier
DPY	Working Days per Year	269	days	Author Estimation
sh	Salary per Hour	16	€	Based on 1200€/month
p_e	Price of Electricity	0.1571	€/kWh	EDP tariff
p_g	Price of Gas	0.0075	€/l	EDP tariff
p_b	Price of Building	30	€/m2	Author Estimation
r	Interest Rate	10	mm	-

4.1.3 Manufacturing Informations

It is necessary to present a possible production line for the case study, where some manufacturing options are selected. For an AM production line, it is only necessary to choose which types of post-processing are appropriate for the production of this part. Figure 4.4 shows a typical line of an additive-produced part. Where the first step is the design of the part using CAD software followed by 3D printer setup, where the operator check. Where the operator checks the raw material deposits and the gas chamber and prepares the machine for printing the part. Then the printer is ready to build the first batch of parts. For post-processing, heat treatment was chosen with the same steps as in conventional manufacture, a sizing correction with EDM, in which it then passes through Hot Isostatic Pressing and finally a surface treatment which in this case is shot peening.

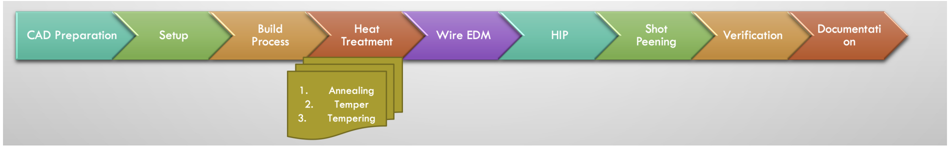


Figure 4.4: Selected Line for Case Study of AM Part

For a forging production line, it is necessary select some manufacturing options, such as cold/hot forging, type of machine, which post-processing is required, among others. Figure 4.5 shows the manufacturing options selected by forging method, the choice of these manufacturing options was consulted with a forging specialist and may differ from the original manufacturing options of the part. So, we opted for a production line used in the Jaime's model [80] because it is a more complete line, with several post-processing and production steps. Note that there are several ways to manufacture the same part, the type of machine selected, the type of forging, and various types of post processing.

After production of the die, Hot Forging was chosen to make the part more malleable for the impacts which it will suffer with the Forge Hammer. After the part takes shape it goes through the heat treatment where it undergoes three types of treatments: the annealing to refine the grain structure followed by a quenching to harden the part and finally a tempering to correct brittle. To file the final edges, Electrical Discharge Machining (EDM) and MultiAxis Mills (MM) cutting processes are chosen. After the part is built, a quality control is performed, where its dimensions of the part are checked.

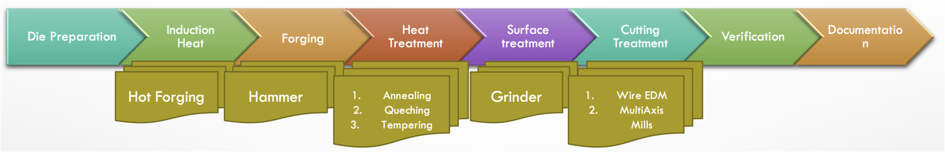


Figure 4.5: Selected Line for Case Study of Forged Part

4.2 Comparison between PBF and DED

This section intends to make a comparative analysis of the two AM technologies. This analysis aims to study where each technology can be more profitable and what are their main economic limitations.

A detailed analysis of the costs is made for each technology for a fixed annual production volume of 50 parts (APV=50). To better understand the differences of each technology we decided to do a sensitivity analysis to the mass of the part to better understand the boundaries of each technology.

(i) Distribution of the costs of PBF and DED

Throught our cost model, we obtained a production cost of 59.60 euros for a DED part and 142.39 euros for a PBF part (for an annual volume of 50 parts).

Figures 4.6 and 4.7, it shows a pie chart where the percentage of the various costs associated with each technology can be observed. In the PBF, the highest percentage refers to the initial investment made to acquire the PBF machine, which corresponds to about 83 % of the production price of the part. The second being the maintenance cost in parallel with the material costs with 6% of the total costs.

On the other hand, in DED the purchase price corresponds to only 43 % of the total production cost. It should be noted that the cost related to the material and energy has a relevant weight in the cost of production of the part, with about 19 % and 23 % respectively. In order to better assess the impact of the cost of the material, a sensitive analysis was made to the variation of the part mass.

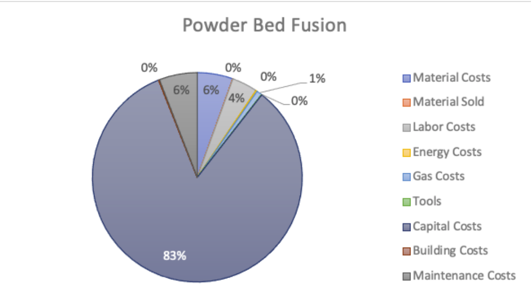


Figure 4.6: Powder Bed Fusion (PBF) distribution costs

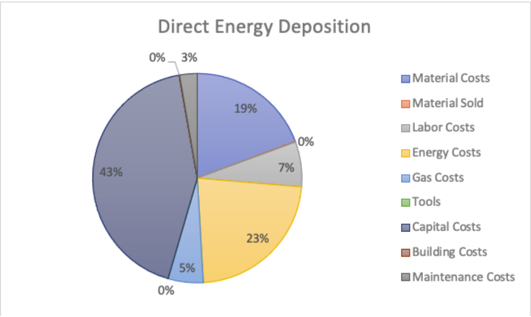


Figure 4.7: Direct Energy Deposition (DED) distribution costs

(ii) Analysis of sensitivity to the variation of the mass of the part

In order to go further in this comparative analysis, knowing that 43% of the costs of DED correspond to the costs of the material, determine the influence on costs of the consumed mass of material is an importante goal. Figure 4.8, it is feasible to conclude that material costs, Energy Costs and Capital Costs are increased, while other costs remain constant. Energy costs increases in function of the mass of the raw material usage. Additionally, the machine costs are dependent on the build time, which it depends of the mass of the part. So, the material mass is the central variable of the DED cost process, as we saw in the 4.2 (i).

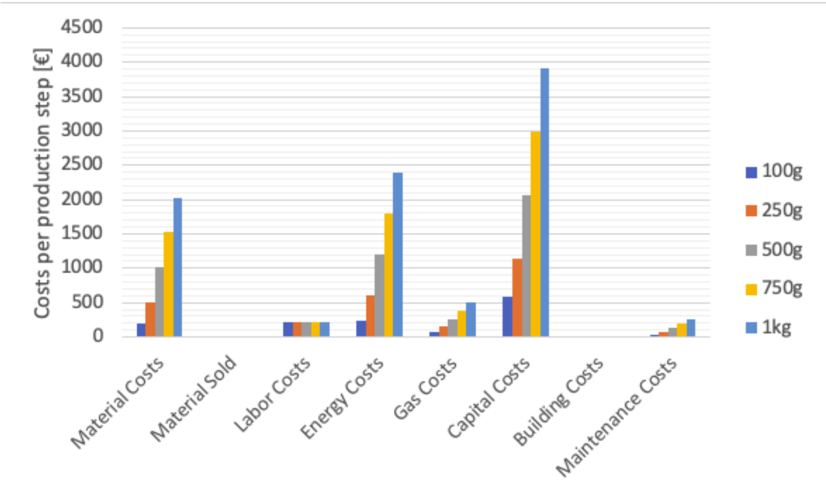


Figure 4.8: Costs of DED process employing a mass of 100g, 250g, 500g and 1kg

In this analysis, it was considered manufacturing the same part where we varied its mass from 100g to 1kg.

Analyzing the lines of the production cost variation by the mass of the part, figure 4.9, it is easily observed that the DED is more profitable than the PBF, however for parts with larger mass (heaviest than 814 grams for this case study) this is no longer so.

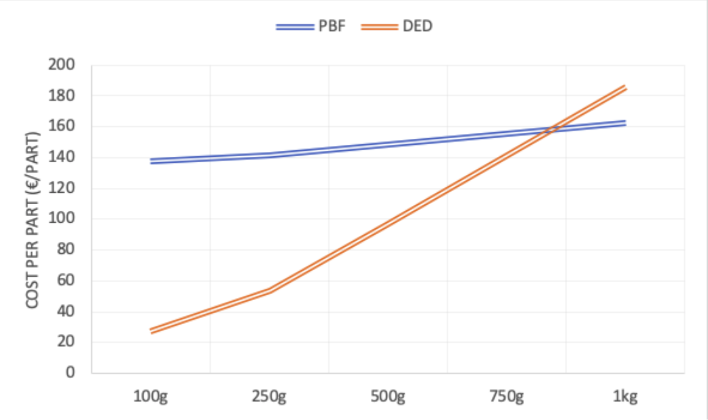


Figure 4.9: Costs of DED and PBF process employing a mass of 100g, 250g, 500g and 1kg

4.3 Comparison between AM and Forging

In order to better understand the limitations of additive manufacturing in aerospace industry, an analysis of each technology was carried out without post processing and compared with a conventional method, forging. In a first step, a variation in the volume of annual production was made in order to see how far additive manufacturing is economically profitable compared to forging. Then, a sensitivity analysis is made to the complexity of the part where an annual volume of 50 identical parts was selected and the complexity factor (F) was varied between 1 (low complexity part), 2 (medium complexity) and 3 (very complexity part). Finally, an uptime sensitivity analysis is performed. This analysis aimed to assess the sensitivity of AM technologies and forging the daily line time available.

(i) Analysis of Cost per Part for different annual production volumes

AM technologies show that the cost of the part is constant with the variation of production volume, the opposite happens with forging. Forging presents high production costs for low volumes, reducing these costs as the number of units produced annually increases. In this case study, the additive manufacturing becomes advantageous for a production volume of 44 parts, in the case of the PBF, and 109 parts, for DED technology. Analyzing the price of each technology for a annual production volume of 50 parts, DED has costs under 60 €, forging has costs around 123€ and PBF has a cost of 142.62 €.

The variation in the price of the forged part is easily justified by the high cost of tools dedicated to this production, such as the high price of a die, for which a high volume of production is necessary to dissolve the costs.

In this analysis, a daily uptime of 8 hours was assumed for the forging equipment and 12 hours for the AM equipment and pre heating equipment. This number is due to the capacity of the machine to produce almost 100 hours in row, being able, in many cases, to print during the night or weekends. These periods, which in other manufacturing processes cannot be accounted for, can be used the 3D printer, since the physical presence of any operator is not necessary in that space time.

Figure 4.10 shows the production cost of a part manufactured by forging, DED and PBF without post-processing with a variation in production volumes.

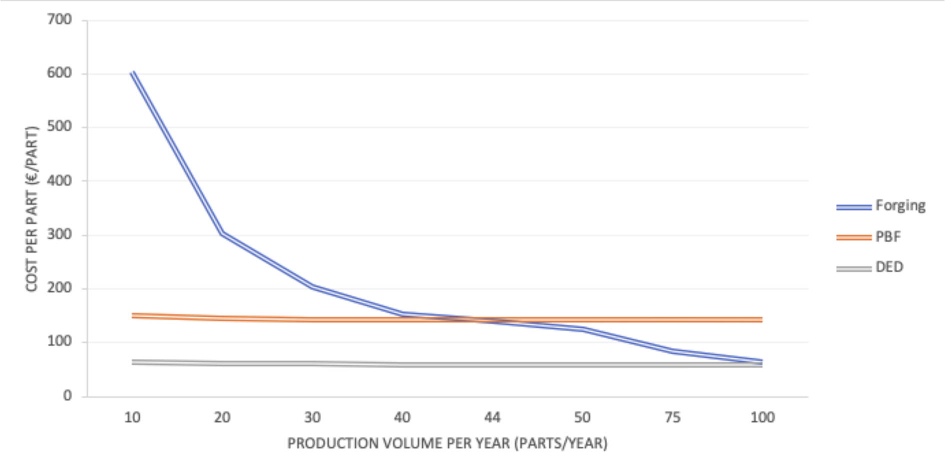


Figure 4.10: Comparison for different production volumes between PBF, DED and Forging

(ii) Machine Uptime sensitivity analysis

The purpose of this analysis is to see the sensitivity of each technology to the number of machine hours available throughout the year. In this analysis it was varied the Line Time Available (LTA) of each technology of 8, 12, 16 and 24 hours. We obtained the results of the graph 4.11, where it is possible to observe that forging the value of each part remains unchanged, due to the fact of the low cycle time of the forging machine, in the order of seconds, which for an Annual Production Volume (APV) of 50 annual good parts, the machine easily produces that amount in less than 1 hour. Thus, a variation of 8-24h of uptime will not influence the cost of manufacturing the part. For this reason, increasing the uptime in forging method will not affect the costs of production of the part.

For AM technologies, this value significantly changes the cost of the part, especially for PBF. The higher this value is, the lower the cost per part value is. A machine that can produce a high number of hours in a row has a greater cost reduction by distributing the costs of the machine over the high numbers of parts produced.

(iii) Analysis of possible technological advances and reduction of acquisition prices

The intensive research that is being developed by several companies and the need to improve the techniques of additive manufacturing may have consequences in the near future. The possible reduction in acquisition prices and the improvement of lasers and printing technologies are on the table for the foreseeable future.

With this, it is important to study the impact that these technologies could suffer in the short term.

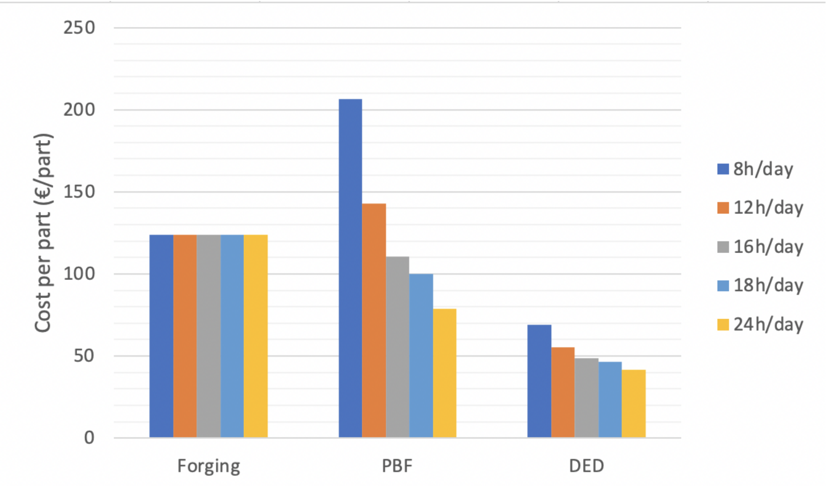


Figure 4.11: Comparison of the uptime variation between PBF, DED and Forging

A study was done where the purchase price of 3D printers was reduced by 10%, 20% and 30% and a reduction in printing speed in the same way.

Figure 4.12: Reduced the purchase price of AM equipment by 10%, 20% and 30%

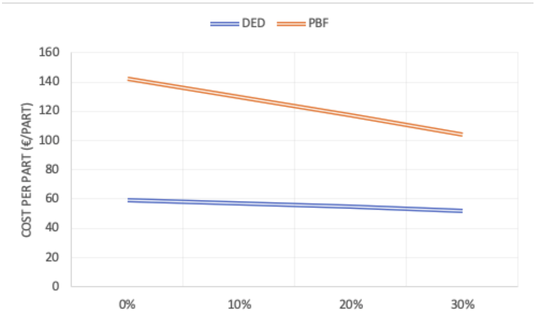


Figure 4.13: Reduced print speed of AM equipment by 10%, 20% and 30%

Analyzing figures 4.12 and 4.13, the PBF is the technology that may suffer the greatest cost reduction per unit production. This is due to the fact that the high cycle time of PBF, an improvement in order to reduce this cycle time will have a significant impact on the production cost of this technology. In the case of DED, this variation in production cost is less, since the cycle time is significantly less than the cycle time of the PBF, and a reduction in cycle times will affect more the technology that has the longest times.

In figure 4.14, a study is made assuming a reduction of about 30 % both in the purchase price of AM equipment and in the printing speed of the same, where the annual production volume was varied. What we can see in relation to figure 4.10 is that these technological advances may bring a greater advantage to additive manufacturing technologies as it can make them more competitive for average production volumes when compared to forging, for example.

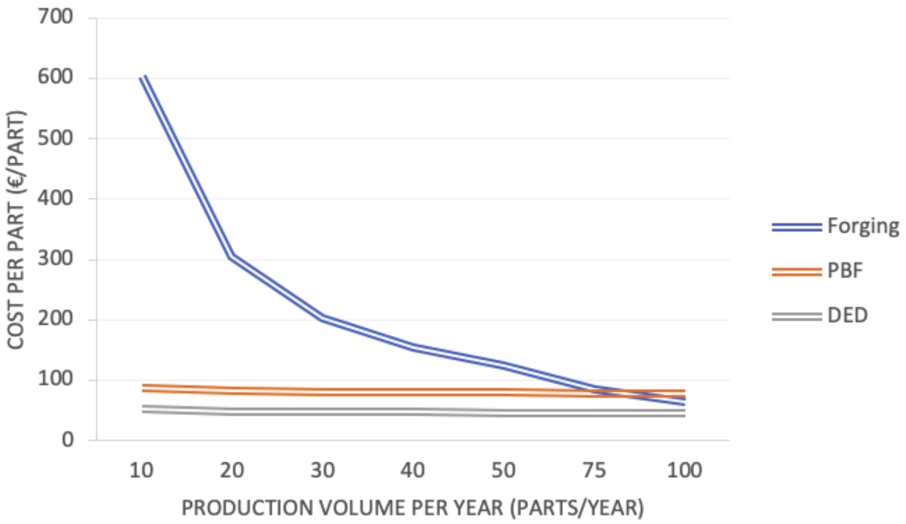


Figure 4.14: Variation of APV for the 3 technologies considering a price reduction and printing speed of 30%

4.4 Post Processing

This section intends to analyze the cost of each stage of the production line. An analysis is made of each post-processing and its contribution to the final price of the part.

The part of our case study and the maintenance lines described in section 5.1.3 are used for a fixed annual volume of good parts of 50 parts.

(i) Additive Manufacturing Production Line

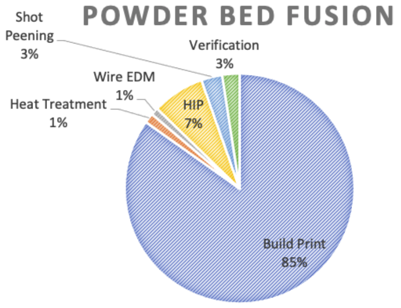


Figure 4.15: Percentage of PBF process steps

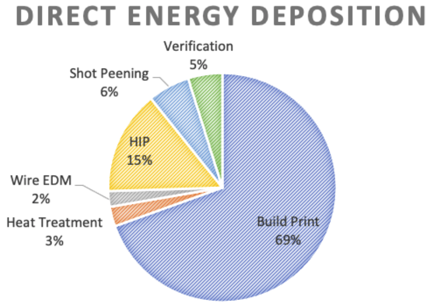


Figure 4.16: Percentage of DED process steps

Table 4.3: Costs of PBF and DED process steps

Prodution Step	DED Line Costs	PBF Line Costs
Build Print	62,15	150,86
Heat Treatment	2,49	2,46
Wire EDM	1,97	1,87
HIP	13,15	13,09
Shot Peening	5,30	5,26
Verification	4,33	4,33
Total	89,40	177,88

In the table 4.3 , the costs of each of the production steps for the additive manufacturing technologies are shown and in the figures 4.15 and 4.16 their contribution to the final cost of the part. Analyzing the cost of the entire production line in our case study, the cost of printing the part has the highest percentage of the total cost, with around 85 % for the PBF and 69% for the DED, which will correspond 25% and 31% of the production line costs to post-processing.

It is important to highlight the high contribution of Hot Isostatic Pressing (HIP), corresponding to 7 % and 15 % for PBF and DED, respectively. The isostatic press is by far the most expensive equipment that corresponds to 2.5 million euros, which means that its contribution to the final part is significant.

(ii)Forging Production Line

Figure 4.17: Costs of each Step in final Part made by forging

Prodution Step	Forging Line Costs
Forging	123,65
Heat Treatment	3,67
Grinder	1,56
Wire EDM	2,01
MultiAxis Mills	8,43
Verification	4,33
Total:	143,65

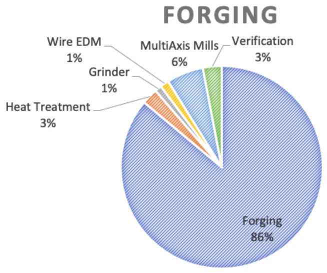


Figure 4.18: Percentages of each Step in final Part made by forging

When comparing the production line with forging, data from table 4.17 and figure 4.18, we observe that this conventional method has a lower post-processing value, about 14 %, than the additive processing methods. It is important to emphasize that there is a greater need for finishing treatment in the case of Additive Manufacturing (AM) parts than by traditional methods, namely removal of substrates, powder sensetization among others.

4.5 Model Validation

The direct comparison between results obtained with this cost model with literature data is shown in table 4.4.

All the results obtained by the model developed in the present thesis dissertation were converted fot the specific cost metric €/cm^3 for a better comparison with the theoretical results.

The data in the table 4.4 were calculated by dividing the cost obtained by the model in euros for an annual production volume of 50 parts and an uptime of 12h.

The PBF was based entirely on the model developed by Sequeira [6], only updating the maintenance values of 3D printer, hence the results increased by about 0.05 %.

DED was compared with a model developed by Baumers et al. [92] where there is a clear decrease in costs, around 77%. This cost difference is easily explained by the purchase price of the raw material, where in the Baumers model the price of the raw material was more than 200 € per kilogram,

Table 4.4: Specific cost estimations comparison with the literature on metallic AM and Forging

Techonology	***System***	***Reference***	***Specific Cost Estimation***
Powder Bed Fusion	Renishaw AM 400	Present Study	4.063 €$/cm^3$
Powder Bed Fusion	Renishaw AM 400	Sequeira et al. [6]	4.041 €$/cm^3$
Direct Energy Deposition	Optomec LENS® 850-R system	Present Study	1.62 €$/cm^3$
Direct Energy Deposition	Laser-sintering system EOSINT M270	Baumers et al. [92]	7.03 €$/cm^3$
Forging	Drop Forging	Present Study	3.52 €$/cm^3$
Forging	Drop Forging	Ribeiro et al. [93]	3.91 €$/cm^3$
Finishing Treatments	Set of Various	Present Study	25-32% of total cost
Finishing Treatments	Set of Various	Mendonça et al. [94]	38% of total cost

while the model developed in this dissertation used an acquisition cost of 30 € per kilogram. Since DED is a technology that is very sensitive to the variation of raw material prices as we saw in the chapter 4, a fact that justifies this high deviation.

In a study developed by Mendonça et al.[94] at Instituto Superior Técnico predicted a cost associated with post-processing of 38%, which included costs of heat treatment, wire erosion and shot peening. For the production of our case study, post-processing corresponds to 25% in the case of DED and 32% in the case of PBF, which includes heat treatment, shot peening, wire EDM and hot isostatic pressing.

5

Environmental Impact

In this chapter, a simplified analysis of the environmental impact is made using the ReCiPe Midpoint (H) method to assess CO2eq emissions to the environment. An analysis is made of the emissions of the both technologies analyzed in this dissection and compared with forging.

5.1 Life Cycle Assessment

Over the past few decades, more emphasis has been placed on assessing potential environmental impacts, which also concerns the development of new technologies. Like any other manufacturing process, additive manufacturing can bring some environmental benefits compared to conventional methods.

To assess the life cycle assessment of each Additive Manufacturing (AM) technology, it is necessary to evaluate all stages of the life cycle, from the extraction of raw material to the end of its life, as shown in figure 5.1.

In this life cycle analysis we will only consider the production of the part and not consider the use nor the end of life. To calculate the environmental impact, the ReCiPe Midpoint (H) version 1.11 method was used, where the total impact received at the midpoint is calculated by adding the environmental impact of the extraction of raw material and the energy impact in the production of the part, as shown in the following equation:

$$TI_m = CF_{RM} + CF_{Energy} \tag{5.1}$$

TI_m is the total impact of the process m, CF_{RM} is the environmental coefficient of the material and the CF_{Energy} is the emission related to the energy expenditure during the process.

The environmental impact of the extraction of raw material is given by the equation:

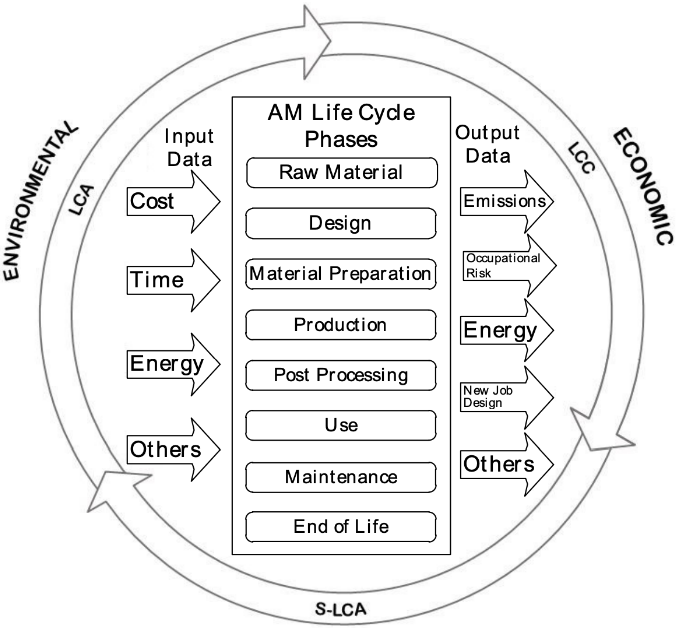


Figure 5.1: Inputs and outputs defined in a product's life cycle

Source: Framework for Life Cycle Sustainability Assessment of Additive Manufacturing [95]

$$CF_{RM} = mass_i * (1 + s_i) * Factor_M - mass_i * s_i * Factor_S \tag{5.2}$$

CF_{RM} is total mass used in the process minus the recycled material left in the process s_i.

The Energy Impact is given by the following equation:

$$CF_{Energy} = EU_i * Factor_E \tag{5.3}$$

EU_i is the energy spent during the process and $Factor_E$ is the amount of CO2 released.

5.2 Goal and Scope definition

The aim of this study is to analyze and compare the environmental impacts associated with additive manufacturing, from the raw material to the end of the manufacturing of our case study. it is important to analyze all stages of production not only to know whether or not they are a real advantage but also to know where to improve.

5.3 Life cycle inventory analysis

The equipment used to fabricate the gear is described in chapter 3. In order to assess the total impact of a production line, the mass and energy used in each stage of the line are needed, the total impact being the sum of all impacts of each process, as shown in the figure 5.2.

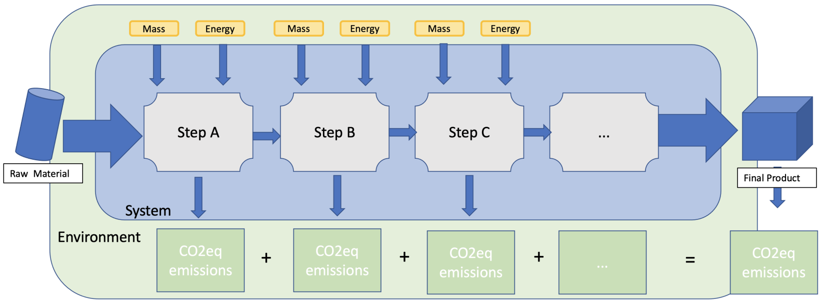


Figure 5.2: Inputs and outputs defined in a product's life cycle

5.4 Case Study

Using the same case study and manufacturing options as chapter 4's, we can complete the table 5.1 with the variables needed to calculate the environmental impact.

Table 5.1: Set of variables for calculating the environmental impact of AM technologies

Variables	**PBF**	**DED**	**Heat Treat**	***EDM***	***HIP***	***Shot Peening***
Waste (%)	8	30	0	5	0	2
Electricity Usage per Part (kWh)	2,01	64.02	6.35	3.49	9.58	0.15
Mass required before Step (kg)	0.3067	0.3692	0.284	0.284	0.2698	0.2644

The calculation of the energy used per part was based on an annual production volume of 50 parts, where the conversion was made to MJ per part.

In other to have a comparison term, it was also calculated Life Cycle Assessment (LCA) for the forging process. The variables necessary to calculate the environmental impact of forging are shown in the table 5.2.

Table 5.2: Set of variables for calculating environmental impact for forging

Variables	**Pre Heat**	**Forging**	**Heat Treat**	***Grinder***	***EDM***	***M. Mills***
Waste (%)	0	30	0	5	5	10
Electricity Usage per Part (kWh)	0.16	0.22	9.92	1.45	5.39	9.17
Mass required before Step (kg)	0.577	0.577	0.4437	0.4437	0.4216	0.400

The necessary constants regarding extraction and recycling of tool steel as well as the constant related to energy use are shown in the table 5.3.

Table 5.3: Set of constants for the calculation of CO2 eq corresponding to tool steel

Variables	**Value**
$Factor_M$	1.92
$Factor_S$	0.206
$Factor_E$	0.211

5.5 Results and Discussion

We made a simplified analysis of the environmental impact caused by each process analyzed in chapters 3 and 4. Table 5.4 shows the total impact of each of them, from the environmental effect related to the exploration of the raw material to the energy used during the process. Note that these values are calculated for the production line, chosen in chapter 4, for each of the manufacturing processes.

Table 5.4: Total Impact of AM technologies and forging in environment

	Mass	**Energy**	**Total**
PBF	0,58	16,40	16,976
DED	0,69	63,49	64,179
Forging	1,06	19,99	21,052

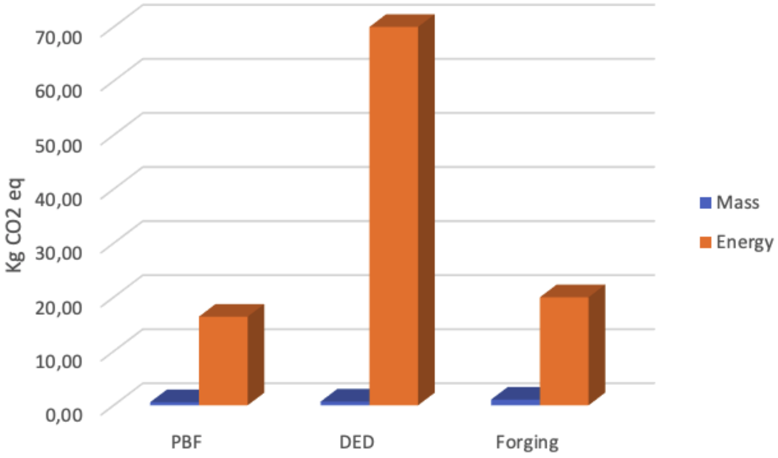


Figure 5.3: Impact of AM technologies and forging in environment

The graph 5.3 represents the impact caused by the extration of the raw material (blue bar) and by the energy waste (orange bar). We can easily observe that for both AM technologies (Direct Energy Deposition (DED) and Powder Bed Fusion (PBF)) and the forging, the impact caused by the mass of the part is a small fraction of the total impact. This happens because the part is relatively small, weighting around 285g. However, for bigger parts we predict that the energetic fraction will be proporcional to the increasing mass, for the AM technologies, while in the case of forging this propotion isn't verified. Forging uses dies and presses, regardless of the size of the part, meaning that the process will be similar unlike AM technologies. With AM technologies, the whole mass of those larger parts will have to be deposited in the printing chamber, which implies a greater energy expenditure.

The experience made by Liu et al. [90], used an Optomec 750, equipped with an 500W IPG fiber laser. The laser beam is generated by the excitation of crystals, here the efficiency is about 30%, which does not require high use of a cooling turbine. On the other hand, the most developed additive technology is PBF and for this reason the equipment already has an energy expenditure comparable to conventional manufacturing.

Regarding the impact related to the extraction of raw materials, we need to take into account the waste of each process. The PBF and DED have scrapt rates of 8 an 30% respectively. It's a relevant difference that does not translate into an environmental impact for two reasons: firstly because the part is small and the percentage related to the extraction of raw material is almost insignificant and secondly because it was considered that the recycling of this scrapt mitigates those same impacts.

Figure 5.4: Impact of AM production lines by production step

	Mass	**Energy**	**Total**
PBF	0,04	1,53	1,57
DED	0,15	65,56	65,71
HT	0,00	4,82	4,82
EDM	0,02	2,65	2,67
HIP	0,01	7,28	7,29
SP	0,01	0,12	0,12

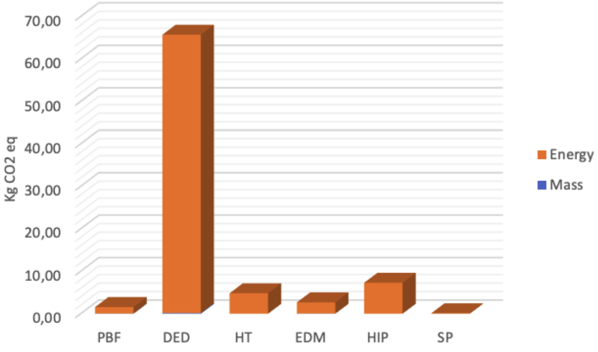


Figure 5.5: Impact of AM production lines by production step

We analyzed the production line proposed in chapter 4's cost model, obtaining the graph 5.5. This cost model only considers the scrapt and energy in each production step.

In this dissection and for this case study, we opted for similar post-processing for the two AM technologies. Due to the high energy consumption that the DED process requires, the post-processing steps have an environmental impact of 23% compared to Build print. Using PBF technology, on the other hand, the greatest impact will correspond to post-processing (since it is a device with less energy expenditure), as shown in table 5.4.

It should be noted that between all the finishing treatments, the Hot Isostatic Pressing (HIP) is the one with the greatest environmental impact due, once again, to the energy expenditure and the heat treatment.

6

Conclusions and Future Work

6.1 Conclusion

Additive manufacturing technologies are increasing the manufacturing options in several industries, providing new possibilities for the construction of parts and bringing some advantages. Additive Manufacturing (AM) is a process that offers a good alternative for the creation of new parts of high complexity as well as the redesigning of existing parts (making them lighter), which is a big advantage for the aerospace industry. This highlights the importance of studying the entire process, from raw material to part finishing processes.

A developed MatLab Tool allows us to analyse the cost of producing parts using different technologies. Most studies and models developed over the years, discard post-processing, emphasizing the printing stage through Metal additive manufacturing (MAM). This model has the particularity of including post-processing treatments and editing the production line for a case study, being a great advantage when dealing with non-static production lines. (production lines that allow us to change the steps of production). They allow us to evaluate the costs of parts produced in unusual ways. The current thesis includes two of the most used AM technologies that produce metal parts, Direct Energy Deposition (DED) and Powder Bed Fusion (PBF), as well as the traditional method of forging.

Comparing both AM technologies with forging in the production of our case study part, it was concluded that AM becomes competitive for a small to medium annual production volume. PBF showed to be profitable for an annual production of "goods" below 44 parts, while the DED is profitable bellow 118 parts compared to forging. The sensitivity of the forging and the complexity of the parts was also analyzed. This study confirmed that the production cost increases with the complexity of the part when forging, whereas in AM technologies, these costs become constant because there are no tools required. The reason for this rise is the increase in the cost of the die and the need to divide complex parts into simpler ones, increasing the number of stations in the production line.

After comparing different AM technologies, we concluded that the DED is very sensitive to the mass of the part, which makes it unprofitable for parts over 814g of mass (compared to the PBF). In addition to the importance of the economic impact analyzed with the cost model, it is known that PBF is a technology that allows for greater detail and resolution in the printing of parts, while DED is a technology through which the printing of the part is substantially faster. Hence, the choice of AM technology cannot be based solely on the cost of production but also on its application purposes.

When analyzing several production lines, it is important to note that post-processing corresponds between 18% - 25% of the final price of our case study (depending on the type of finishing treatment chosen and the type of AM technology being used).

With the evolution of these technologies, both the acquisition price and printing time may be reduced, which will make AM more competitive (with PBF being the most benefited).

Although AM technologies are economically competitive for lower production volumes, they present significant energy costs that have caused a greater environmental impact, namely the DED. PBF allows us to reduce the waste of the raw material and present energy impacts similar to conventional processes, namely the forging analyzed also in this dissertation.

The integration of this cost model in a company may be an important tool to support the decision of the production method of a given part. It offers 3 alternative choices between the most used methods in the production of metal parts and some possibilities of post-processing that may allow the user to get a hold of all the steps of a production part.

6.2 Future Work

The analysis and development of the current thesis will require more practical cases to estimate and validate all the costs of the 3 abovementioned manufacturing processes.

It may be required to add new AM technologies for metal parts such as Binder Jetting, which allows us to decrease build time and print objects with colours.

It may be useful to replace the input of the dimensions of the parts with the Computer Aided Design (CAD) of the model, where it makes an estimate of the optimization of the parts.

Bibliography

[1] G. Camelia, S. Mihai *et al.*, “The economic and social benefits of air transport,” *Ovidius University Annals, Economic Sciences Series*, vol. 10, no. 1, pp. 60–66, 2010.

[2] E. L. Synnes and T. Welo, “Bridging the gap between high and low-volume production through enhancement of integrative capabilities,” *Procedia Manufacturing*, vol. 5, pp. 26–40, 2016.

[3] S. Mellor, L. Hao, and D. Zhang, “Additive manufacturing: A framework for implementation,” *International journal of production economics*, vol. 149, pp. 194–201, 2014.

[4] R. Liu, Z. Wang, T. Sparks, F. Liou, and J. Newkirk, “Aerospace applications of laser additive manufacturing,” in *Laser additive manufacturing*. Elsevier, 2017, pp. 351–371.

[5] B. Lyons, “Additive manufacturing in aerospace: Examples and research outlook,” *The Bridge*, vol. 44, no. 3, 2014.

[6] D. Sequeira, “Metal additive manufacturing in aeronautics: a life cycle cost perspective,” Ph.D. dissertation, 2019.

[7] J.-Y. Lee, J. An, and C. K. Chua, “Fundamentals and applications of 3d printing for novel materials,” *Applied Materials Today*, vol. 7, pp. 120–133, 2017.

[8] M. Cotteleer and J. Joyce, “3d opportunity: Additive manufacturing paths to performance, innovation, and growth,” *Deloitte Review*, vol. 14, pp. 5–19, 2014.

[9] P. J. Bártolo and I. Gibson, “History of stereolithographic processes,” in *Stereolithography*. Springer, 2011, pp. 37–56.

[10] D. L. Bourell, “Perspectives on additive manufacturing,” *Annual Review of Materials Research*, vol. 46, 2016.

[11] T. Wohlers and T. Gornet, “History of additive manufacturing,” *Wohlers report*, vol. 24, no. 2014, p. 118, 2014.

[12] T. Birtchnell, J. Urry, C. Cook, and A. Curry, “Freight miles: the impact of 3d printing on transport and society,” 2013.

[13] G. Warwick, “3-d-printed parts prove beneficial for airbus and ula,” *Aviation Week & Space Technology*, vol. 177, no. 20, p. 1, 2015.

[14] R. O. Walton, “The 6th mode of transportation,” *Journal of Transportation Management*, vol. 25, no. 1, p. 6, 2014.

[15] R. Bäßler, “Additive manufacturing of metals–from fundamental technology to rocket nozzles, medical implants, and custom jewelry (book review),” 2018.

[16] J. Coykendall, M. Cotteleer, J. Holdowsky, and M. Mahto, “3d opportunity in aerospace and defense: Additive manufacturing takes flight,” *A Deloitte series on additive manufacturing*, vol. 1, 2014.

[17] J. A. P. d. Santos, “Cost estimation model for the directed energy deposition process adopting an activity-based approach,” Ph.D. dissertation, 2018.

[18] I. Gibson, D. W. Rosen, B. Stucker *et al.*, *Additive manufacturing technologies*. Springer, 2014, vol. 17.

[19] lboro. Material jetting. [Online]. Available: https://www.lboro.ac.uk/research/amrg/about/the7categoriesofadditivemanufacturing/materialjetting/

[20] A. Vasotsis. Introduction to material jetting 3d printing. [Online]. Available: https://www.3dhubs.com/knowledge-base/introduction-material-jetting-3d-printing/

[21] P. K. Gokuldoss, S. Kolla, and J. Eckert, “Additive manufacturing processes: Selective laser melting, electron beam melting and binder jetting—selection guidelines,” *Materials*, vol. 10, no. 6, p. 672, 2017.

[22] lboro. Binder jet. [Online]. Available: https://www.lboro.ac.uk/research/amrg/about/the7categoriesofadditivemanufacturing/binderjetting/

[23] M. Ziaee and N. B. Crane, “Binder jetting: A review of process, materials, and methods,” *Additive Manufacturing*, vol. 28, pp. 781–801, 2019.

[24] R. Udroiu, “Powder bed additive manufacturing systems and its applications.” *Academic journal of manufacturing engineering*, vol. 10, no. 4, 2012.

[25] 3dilla. Powder bed fusion. [Online]. Available: https://pt.3dilla.com/impressora-3d/dmls/

[26] lboro. Powder bed fusion. [Online]. Available: https://www.lboro.ac.uk/research/amrg/about/the7categoriesofadditivemanufacturing/powderbedfusion/

[27] S. M. Wagner and R. O. Walton, “Additive manufacturing’s impact and future in the aviation industry,” *Production Planning & Control*, vol. 27, no. 13, pp. 1124–1130, 2016.

[28] N. Shamsaei, A. Yadollahi, L. Bian, and S. M. Thompson, “An overview of direct laser deposition for additive manufacturing; part ii: Mechanical behavior, process parameter optimization and control,” *Additive Manufacturing*, vol. 8, pp. 12–35, 2015.

[29] D. Bourell, J. P. Kruth, M. Leu, G. Levy, D. Rosen, A. M. Beese, and A. Clare, “Materials for additive manufacturing,” *CIRP Annals*, vol. 66, no. 2, pp. 659–681, 2017.

[30] lboro. Direct energy deposition. [Online]. Available: https://www.lboro.ac.uk/research/amrg/about/the7categoriesofadditivemanufacturing/directedenergydeposition/

[31] C. V. Direct energy deposition. [Online]. Available: https://www.3dnatives.com/en/directed-energy-deposition-ded-3d-printing-guide-100920194/#!

[32] D. Peterson. Benefits and limitations of additive manufacturing. [Online]. Available: https://control.com/technical-articles/Benefits-and-Limitations-of-Additive-Manufacturing/

[33] X. He and J. Mazumder, “Transport phenomena during direct metal deposition,” *Journal of Applied Physics*, vol. 101, no. 5, p. 053113, 2007.

[34] E. Toyserkani, A. Khajepour, and S. F. Corbin, *Laser cladding*. CRC press, 2004.

[35] A. Saboori, D. Gallo, S. Biamino, P. Fino, and M. Lombardi, “An overview of additive manufacturing of titanium components by directed energy deposition: microstructure and mechanical properties,” *Applied Sciences*, vol. 7, no. 9, p. 883, 2017.

[36] A. Staff. Pros and cons of additive manufacturing. [Online]. Available: http://compositesmanufacturingmagazine.com/2014/10/pros-cons-additive-manufacturing/2/

[37] horizontechonoly. 3 advantages disadvantages of additive manufacturing process. [Online]. Available: https://www.horizontechnology.biz/blog/advantages-and-disadvantages-of-additive-manufacturing-process-vs-powder-metallurgy

[38] R. Huang, M. Riddle, D. Graziano, J. Warren, S. Das, S. Nimbalkar, J. Cresko, and E. Masanet, “Energy and emissions saving potential of additive manufacturing: the case of lightweight aircraft components,” *Journal of Cleaner Production*, vol. 135, pp. 1559–1570, 2016.

[39] N. Boubekri and M. Alqahtani, “Economics of additive manufacturing,” *Int. J. Adv. Mech. Automob. Eng*, vol. 2, pp. 12–14, 2015.

[40] S. A. Tofail, E. P. Koumoulos, A. Bandyopadhyay, S. Bose, L. O’Donoghue, and C. Charitidis, “Additive manufacturing: scientific and technological challenges, market uptake and opportunities,” *Materials today*, vol. 21, no. 1, pp. 22–37, 2018.

[41] T. Pereira, J. V. Kennedy, and J. Potgieter, “A comparison of traditional manufacturing vs additive manufacturing, the best method for the job,” *Procedia Manufacturing*, vol. 30, pp. 11–18, 2019.

[42] N. Loh and K. Sia, “An overview of hot isostatic pressing,” *Journal of Materials Processing Technology*, vol. 30, no. 1, pp. 45–65, 1992.

[43] D. Herzog, V. Seyda, E. Wycisk, and C. Emmelmann, “Additive manufacturing of metals,” *Acta Materialia*, vol. 117, pp. 371–392, 2016.

[44] C. Machining. Subtractive manufacturing vs. additive manufacturing. [Online]. Available: https://xometry.de/en/subtractive-manufacturing-vs-additive-manufacturing/

[45] E. M. Trent and P. K. Wright, *Metal cutting*. Butterworth-Heinemann, 2000.

[46] K. Lange, "Handbook of metal forming," *McGraw-Hill Book Company, 1985,*, p. 1216, 1985.

[47] G. T. Halmos, *Roll forming handbook*. Crc Press, 2005.

[48] Azom. History and key developments in the metals forging industry. [Online]. Available: https://www.azom.com/article.aspx?ArticleID=2195

[49] M. Standridge. Aerospace materials — past, present, and future. [Online]. Available: https://www.aerospacemanufacturinganddesign.com/article/amd0814-materials-aerospace-manufacturing/

[50] S. . T. A. Report, "Metal forging market size," 2020.

[51] M. C. Hall, G. Prayag, P. Fieger, and D. Dyason, "Beyond panic buying: consumption displacement and covid-19," *Journal of Service Management*, 2020.

[52] E. D. d. Souza, "Estudo comparativo para fabricação de peças aeronáuticas: forjamento x usinagem," 2015.

[53] Forging.com. Forging process. [Online]. Available: https://elearningatria.files.wordpress.com/2013/10/mp3_unit3_forging_final.pdf

[54] D. A. Smith, *Die design handbook*. Society of Manufacturing Engineers, 1990.

[55] G. Forge. Cold, warm, and hot forging: Whats the difference? [Online]. Available: https://www.qcforge.com/forging-knowledge/forging-benefits/hot-forging/

[56] W. E. Bryson, "Heat treatment, selection, and application of tool steels," 2005.

[57] S. Forging. Open die forging vs. closed die forging. [Online]. Available: http://www.steelforging.org/open-die-forging-vs-closed-die-forging/

[58] T. Altan, G. Ngaile, and G. Shen, *Cold and hot forging: fundamentals and applications*. ASM international, 2004, vol. 1.

[59] X. Huang, N. Hansen, and N. Tsuji, "Hardening by annealing and softening by deformation in nanostructured metals," *Science*, vol. 312, no. 5771, pp. 249–251, 2006.

[60] H. El-Hofy, *Fundamentals of machining processes: conventional and nonconventional processes*. CRC press, 2018.

[61] H. Tominaga, T. Takayama, Y. Ogura, and T. Yamaguchi, "Electrode wire for use in electric discharge machining and process for preparing same," Aug. 11 1987, uS Patent 4,686,153.

[62] K. P. Rajurkar, M. Sundaram, and A. Malshe, "Review of electrochemical and electrodischarge machining," *Procedia Cirp*, vol. 6, pp. 13–26, 2013.

[63] S. Son, T. Kim, S. E. Sarma, and A. Slocum, “A hybrid 5-axis cnc milling machine,” *Precision Engineering*, vol. 33, no. 4, pp. 430–446, 2009.

[64] T. Saleh and R. Bahar, “1.13 elid grinding and edm for finish machining,” *Comprehensive materials finishing*, pp. 364–407, 2017.

[65] F. Czerwinski, “Thermochemical treatment of metals,” *Heat Treatment–Conventional and Novel Applications*, vol. 5, pp. 73–112, 2012.

[66] S. Malkin, “Grinding of metals: theory and application,” *Journal of Applied Metalworking*, vol. 3, no. 2, pp. 95–109, 1984.

[67] M. Meo and R. Vignjevic, “Finite element analysis of residual stress induced by shot peening process,” *Advances in Engineering Software*, vol. 34, no. 9, pp. 569–575, 2003.

[68] G. Majzoobi, R. Azizi, and A. A. Nia, “A three-dimensional simulation of shot peening process using multiple shot impacts,” *Journal of Materials Processing Technology*, vol. 164, pp. 1226–1234, 2005.

[69] E. Maawad, H. G. Brokmeier, and L. Wagner, “Texture gradients in shot peened ti-2.5 cu,” in *Solid State Phenomena*, vol. 160. Trans Tech Publ, 2010, pp. 141–146.

[70] Y. Kato, M. Omiya, and H. Hoshino, “Modelling of particle behaviour in shot peening process,” *Journal of Mechanical Engineering and Automation*, vol. 4, no. 3, pp. 83–91, 2014.

[71] W. L. Group. Shot peening. [Online]. Available: https://www.wheelabratorgroup.com/pt-pt/my-application/application-by-process/what-is-shot-peening

[72] H. Atkinson and S. Davies, “Fundamental aspects of hot isostatic pressing: an overview,” *Metallurgical and Materials Transactions A*, vol. 31, no. 12, pp. 2981–3000, 2000.

[73] R. Chattopadhyay, *Hot Isostatic Press (HIP)*. Springer, 2004, vol. 17.

[74] E. Atzeni and A. Salmi, “Economics of additive manufacturing for end-usable metal parts,” *The International Journal of Advanced Manufacturing Technology*, vol. 62, no. 9-12, pp. 1147–1155, 2012.

[75] D. S. Thomas and S. W. Gilbert, “Costs and cost effectiveness of additive manufacturing,” *NIST special publication*, vol. 1176, p. 12, 2014.

[76] N. Hopkinson and P. Dicknes, “Analysis of rapid manufacturing—using layer manufacturing processes for production,” *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science*, vol. 217, no. 1, pp. 31–39, 2003.

[77] G. Costabile, M. Fera, F. Fruggiero, A. Lambiase, and D. Pham, “Cost models of additive manufacturing: A literature review,” *International Journal of Industrial Engineering Computations*, vol. 8, no. 2, pp. 263–283, 2017.

[78] M. Ruffo, C. Tuck, and R. Hague, “Cost estimation for rapid manufacturing-laser sintering production for low to medium volumes,” *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, vol. 220, no. 9, pp. 1417–1427, 2006.

[79] M. Ruffo and R. Hague, “Cost estimation for rapid manufacturing’simultaneous production of mixed components using laser sintering,” *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, vol. 221, no. 11, pp. 1585–1591, 2007.

[80] R. E. Laureijs, J. B. Roca, S. P. Narra, C. Montgomery, J. L. Beuth, and E. R. Fuchs, “Metal additive manufacturing: cost competitive beyond low volumes,” *Journal of Manufacturing Science and Engineering*, vol. 139, no. 8, 2017.

[81] E. R. Fuchs, F. R. Field, R. Roth, and R. E. Kirchain, “Plastic cars in china? the significance of production location over markets for technology competitiveness in the united states versus the people’s republic of china,” *International Journal of Production Economics*, vol. 132, no. 1, pp. 79–92, 2011.

[82] ——, “Strategic materials selection in the automobile body: Economic opportunities for polymer composite design,” *Composites science and technology*, vol. 68, no. 9, pp. 1989–2002, 2008.

[83] E. R. Fuchs and R. E. Kirchain, “Design for location: The impact of manufacturing offshore on technology competitiveness in the optoelectronics industry.” Georgia Institute of Technology, 2009.

[84] E. R. Fuchs, R. E. Kirchain, and S. Liu, “The future of silicon photonics: Not so fast? insights from 100g ethernet lan transceivers,” *journal of Lightwave Technology*, vol. 29, no. 15, pp. 2319–2326, 2011.

[85] L. COLTRO, A. Mourad, E. Garcia, G. Queiroz, J. Gatti, and S. Jaime, “Avaliação do ciclo de vida como instrumento de gestão,” *Campinas: Cetea/Ital*, vol. 1, 2007.

[86] J. R. Sepúlveda, “Towards a methodological tool for the integral evaluation of the sustainability of a biocomposite material: A case study,” *DOCTORAL THESIS PROPOSAL*, vol. 1, 2017.

[87] L. Golsteijn. 3recipe. [Online]. Available: https://pre-sustainability.com/articles/recipe/

[88] R. C. to health and sustainability. Lcia: the recipe model. [Online]. Available: https://www.rivm.nl/en/life-cycle-assessment-lca/recipe

[89] S. A. Martin Listén, “Life cycle impact assessment: A comparison of three contemporary methodologies,” 2014.

[90] Z. Liu, C. Li, X. Fang, and Y. Guo, “Energy consumption in additive manufacturing of metal parts,” *Procedia Manufacturing*, vol. 26, pp. 834–845, 2018.

[91] M. Ahlfors, “Cost effective hot isostatic pressing: A cost calculation study for mim parts,” *Quintus*, vol. 6, no. 6, pp. 1–6, 2018.

[92] M. Baumers, C. Tuck, R. Wildman, I. Ashcroft, E. Rosamond, and R. Hague, “Combined build-time, energy consumption and cost estimation for direct metal laser sintering,” in *From Proceedings of Twenty Third Annual International Solid Freeform Fabrication Symposium—An Additive Manufacturing Conference*, vol. 13, 2012.

[93] I. Ribeiro, J. Kaufmann, A. Schmidt, P. Peças, E. Henriques, and U. Götze, “Fostering selection of sustainable manufacturing technologies–a case study involving product design, supply chain and life cycle performance,” *Journal of Cleaner Production*, vol. 112, pp. 3306–3319, 2016.

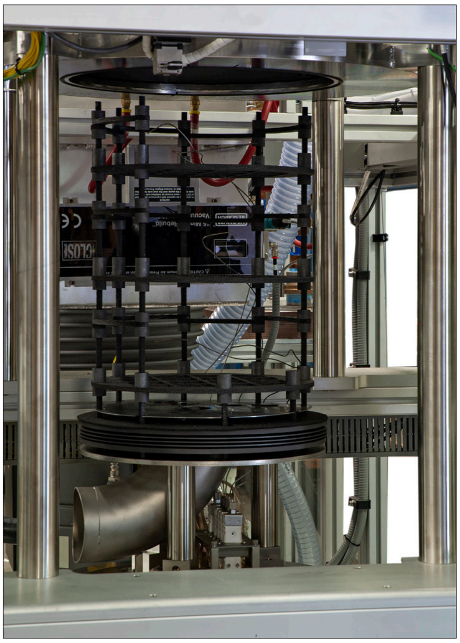
[94] A. R. e. J. M. Marta Gonçalves, “Modelo de custo para fabricação aditiva em metal: Aplicação no setor aeroespacial,” 2019.

[95] I. Ribeiro, F. Matos, C. Jacinto, H. Salman, G. Cardeal, H. Carvalho, R. Godina, and P. Peças, “Framework for life cycle sustainability assessment of additive manufacturing,” *Sustainability*, vol. 12, no. 3, p. 929, 2020.

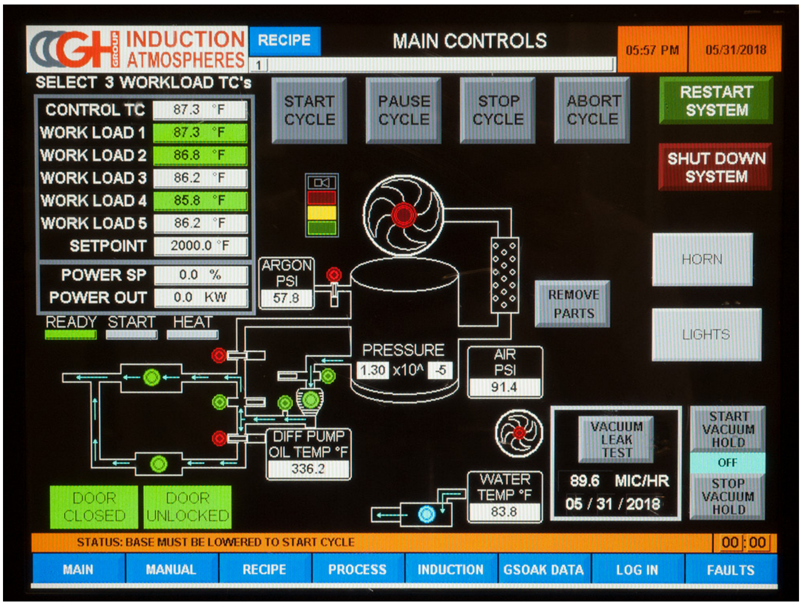
A

Title of AppendixA

GH IA Vacuum Furnaces



Specification	Model VF-35
Hot Zone Size - id x h	12 x16 in. *(305 x 407 mm)*
Hot Zone Volume	1.0 cu ft. *(0.0283 m^3)*
Max. Operating Temperature	3200°F *(1760°C)* *optional three-zone control +/-010°F
Temperature Uniformity	+/- 15°F at 2200°F (*+/- 8°C at 1204°C)*
Time to 1900°F (1038°C)	15 min
Max Parts Weight (lb)	60 lb *(27.2 kg)*
Power Usage (kwh)	17
Gas Usage	16 cu ft. *(0.453 m^3)*
Typical Hourly Running Cost	$5.13
Dimensions (W x D x H)	6 x 5 x 8 ft. *(1829 x 1524 x 2438 mm)*
Water Required:	30 gpm @40 psi differential *(113.6 lpm @117 kg/sq cm. differential)*
Circuit Breaker Size (amp)	100
Shipping Weight	2000 lbs. *(907.2 kg)*



CONTROL TC 87.3 °F
WORK LOAD 1 87.3 °F
WORK LOAD 2 86.8 °F
WORK LOAD 3 86.2 °F
WORK LOAD 4 85.8 °F
WORK LOAD 5 86.2 °F
SETPOINT 2000.0 °F
POWER SP 0.0 %
POWER OUT 0.0 KW
ARGON PSI 57.8
PRESSURE 1.30 x10^ -5
AIR PSI 91.4
DIFF PUMP OIL TEMP °F 336.2
WATER TEMP °F 83.8
89.6 MIC/HR
05 / 31 / 2018
STATUS: BASE MUST BE LOWERED TO START CYCLE
00 : 00

To permit easy loading, the part handling mechanisms on GH IA vacuum furnaces open at the base of the system, then automatically raise the parts up into the vacuum chamber and heating coil, and finally lower the parts back down to base level for unloading. The chambers are mounted on heavy duty frames that house all the required equipment for vacuum, atmospheric and system control, as well as the induction heating station.

Real time monitoring and SPC are a snap with the optional LAN interface or digital chart recorder; data may be stored and sent directly to your desktop. The standard thermocouple controls record all chamber temperatures; individual part temperatures may be controlled and monitored with the optional optical pyrometer.

To maximize operator safety, GH IA vacuum furnace heating systems are fully isolated. Safety interlocks protect access to the vacuum chamber and manual controls.

Other operator safety features include a light curtain, emergency stop and other warning systems built into the software and hardware.

Protected under US Patent 6,649,887 and 7724045. Other patents pending.

35 Industrial Park Circle • Rochester, NY USA 14624
Tel: 585.368.2120 • Fax: 585.368.2123
www.gh-ia.com

▪ GLF PRESSES TECHNICAL DATA (STANDARD)

	GLF 750V	GLF 1000V	GLF 1300V	GLF 1600V	GLF 1800V	GLF 2000V
Press capacity (nominal force) [kN]	7,500	10,000	13,000	16,000	18,000	20,000
Stroke rate (cont.) [mm^{-1}]	100	100	90	85	85	85
Stroke rate (thermal) Standard | KERS [mm^{-1}]	30	22	22	15 | 30	15 | 30	15 | 30
Slide stroke [mm]	200	230	230	280	280	300
Slide adjustment [mm]	10	16	16	16	16	16
Distance Bed/Slide (max.) [mm]	600	700	900	1,100	1,100	1,200
Frontal light between uprights [mm]	750	1,000	1,000	1,100	1,100	1,300
Side light between uprights [mm]	550	720	750	850	850	960
Ram Table size (L-R x F-B) [mm]	710 x 850	890 x 1,070	890 x 1,070	970 x 1,200	970 x 1,200	1,200 x 1,300
Bed area (L-R x F-B) [mm]	750 x 950	1,000 x 1,100	1,000 x 1,100	1,100 x 1,250	1,100 x 1,250	1,300 x 1,300
Main motor power [kW]	45	75	90	110	132	200
Machine weight [kg]	38,000	64,000	75,000	115,000	120,000	140,000

	GLF 2500R	GLF 3150R	GLF 4000R	GLF 5000R	GLF 6300R	GLF 8000R
Press capacity (nominal force) [kN]	25,000	31,500	40,000	50,000	63,000	80,000
Stroke rate (cont.) [mm^{-1}]	70	70	55	50	47	45
Stroke rate (thermal) Standard | KERS [mm^{-1}]	15 | 30	13 | 24	12 | 24	12 | 24	10 | 20	8 | 20
Slide stroke [mm]	340	350	450	400	430	500
Slide adjustment [mm]	20	20	20	20	25	25
Distance Bed/Slide (max.) [mm]	1,500	1,500	1,600	1,600	1,600	1,600
Frontal light between uprights [mm]	1,400	1,400	1,600	1,600	1,800	2,000
Side light between uprights [mm]	960	1,250	1,850	1,150	1,300	1,300
Ram Table size (L-R x F-B) [mm]	1,300 x 1,460	1,520 x 1,700	1,520 x 1,900	1,510 x 1,900	1,650 x 2,200	1,700 x 2,200
Bed area (L-R x F-B) [mm]	1,360 x 1,450	1,630 x 1,700	1,600 x 2,200	1,600 x 1,800	1,800 x 2,200	1,800 x 2,200
Main motor power [kW]	250	250	315	315	355	500
Machine weight [kg]	200,000	250,000	330,000	360,000	600,000	640,000

1500 Ton fechar forjamento martelo máquina de forjamento a quente de aquecimento de indução

FOB **Referência** Preço: Obter Cotação Imediata

9 800,00 US$ - 158 000,00 US$ / Peça | 1 Peça/Peças (Min. Ordem)

Promoção para clientes novos
Até US$ 60 de desconto nas taxas de transação das 3 primeiras compras

Número do Mod... YHA3

Garantia: **1 ANO** para o equipamento

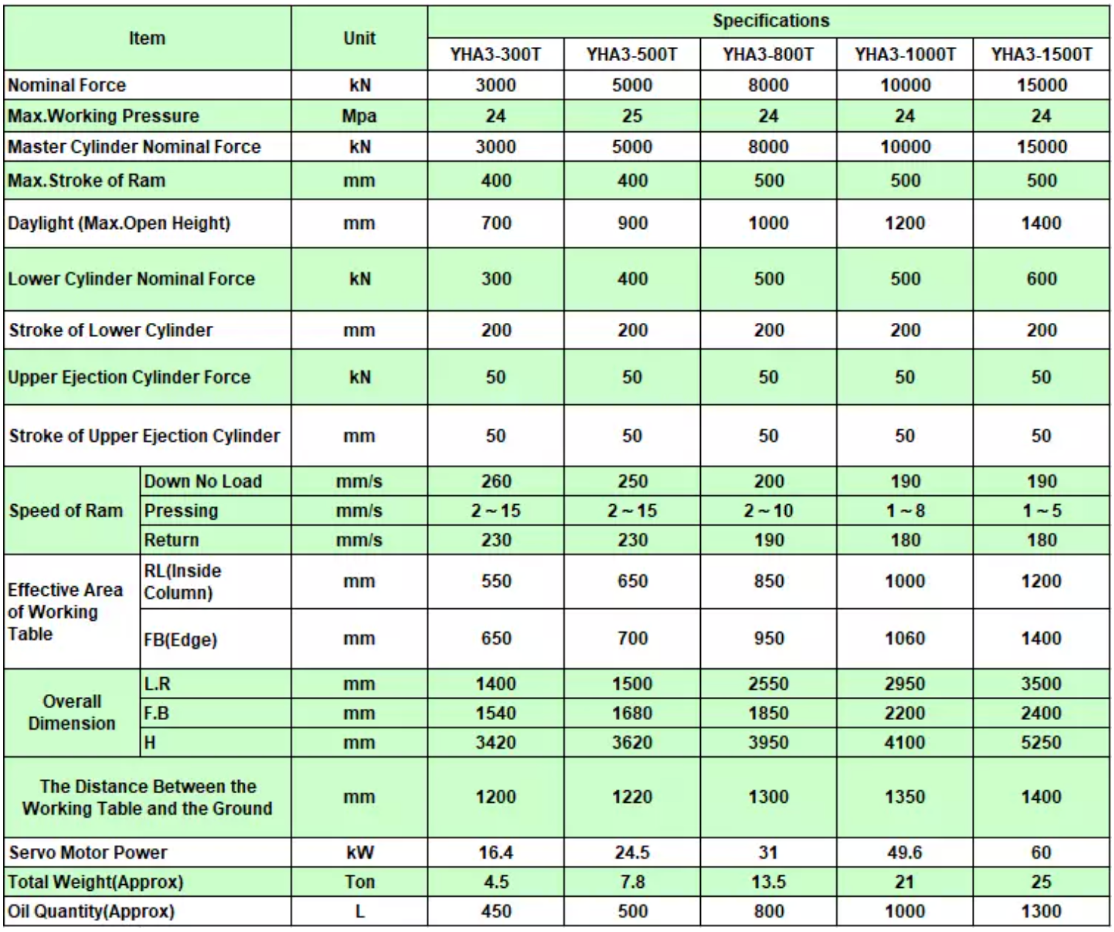
Tempo de execu...

Quantidade(Peças)	1 - 30	>30
Tempo estimado (dias)	35	Negociável

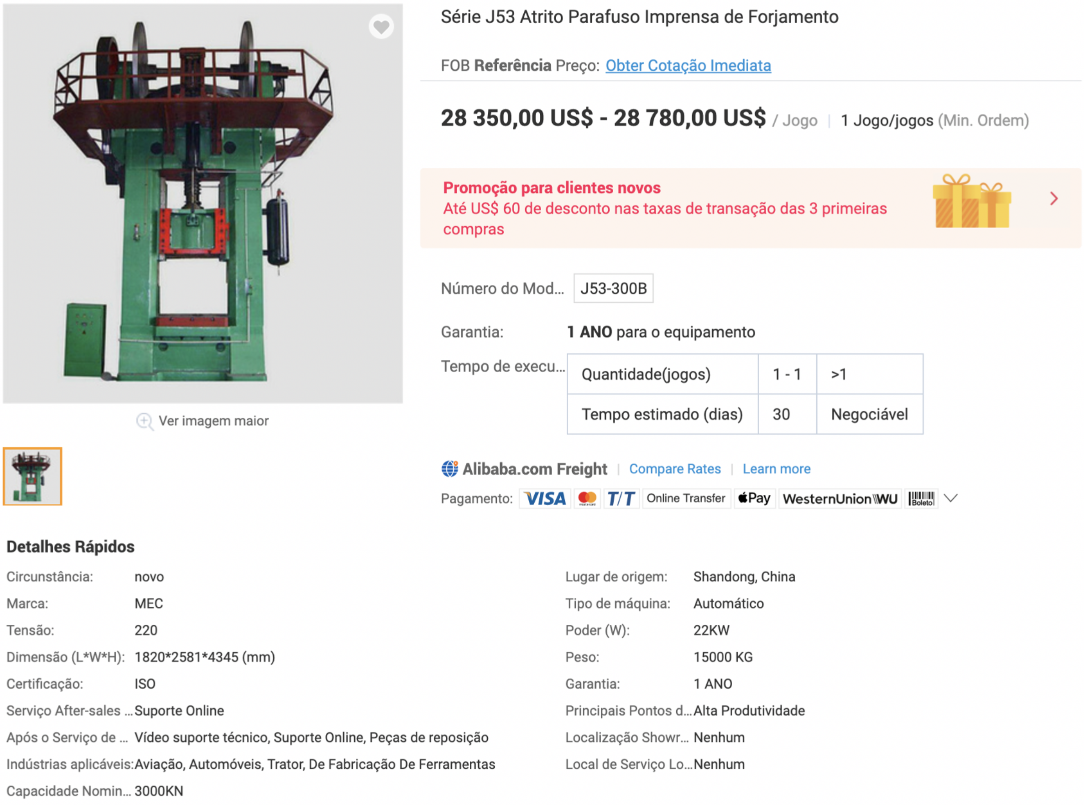
Personalização: Logotipo personalizado (Min. Order: 1 Peças)
Embalagem personalizada (Min. Order: 1 Peças) Mais

Amostras: 1 000,00 US$ /Peça | 1 Peça (Min. Ordem) | Comprar amostras

Especificação



Item		Unit	Specifications				
			YHA3-300T	YHA3-500T	YHA3-800T	YHA3-1000T	YHA3-1500T
Nominal Force		kN	3000	5000	8000	10000	15000
Max.Working Pressure		Mpa	24	25	24	24	24
Master Cylinder Nominal Force		kN	3000	5000	8000	10000	15000
Max.Stroke of Ram		mm	400	400	500	500	500
Daylight (Max.Open Height)		mm	700	900	1000	1200	1400
Lower Cylinder Nominal Force		kN	300	400	500	500	600
Stroke of Lower Cylinder		mm	200	200	200	200	200
Upper Ejection Cylinder Force		kN	50	50	50	50	50
Stroke of Upper Ejection Cylinder		mm	50	50	50	50	50
Speed of Ram	Down No Load	mm/s	260	250	200	190	190
	Pressing	mm/s	2～15	2～15	2～10	1～8	1～5
	Return	mm/s	230	230	190	180	180
Effective Area of Working Table	RL(Inside Column)	mm	550	650	850	1000	1200
	FB(Edge)	mm	650	700	950	1060	1400
Overall Dimension	L.R	mm	1400	1500	2550	2950	3500
	F.B	mm	1540	1680	1850	2200	2400
	H	mm	3420	3620	3950	4100	5250
The Distance Between the Working Table and the Ground		mm	1200	1220	1300	1350	1400
Servo Motor Power		kW	16.4	24.5	31	49.6	60
Total Weight(Approx)		Ton	4.5	7.8	13.5	21	25
Oil Quantity(Approx)		L	450	500	800	1000	1300



Série J53 Atrito Parafuso Imprensa de Forjamento

FOB **Referência** Preço: Obter Cotação Imediata

28 350,00 US$ - 28 780,00 US$ / Jogo | 1 Jogo/jogos (Min. Ordem)

Promoção para clientes novos
Até US$ 60 de desconto nas taxas de transação das 3 primeiras compras

Número do Mod... J53-300B

Garantia: **1 ANO** para o equipamento

Tempo de execu...

Quantidade(jogos)	1 - 1	>1
Tempo estimado (dias)	30	Negociável

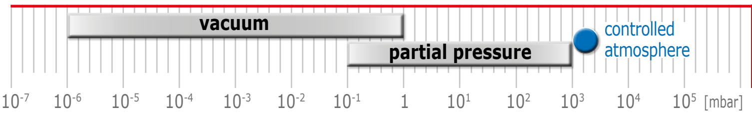
Ver imagem maior

Alibaba.com Freight | Compare Rates | Learn more

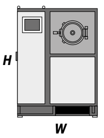
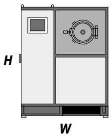
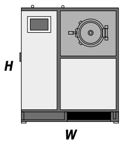
Pagamento: VISA T/T Online Transfer Pay WesternUnion WU Boleto

Detalhes Rápidos

Circunstância:	novo	Lugar de origem:	Shandong, China
Marca:	MEC	Tipo de máquina:	Automático
Tensão:	220	Poder (W):	22KW
Dimensão (L*W*H):	1820*2581*4345 (mm)	Peso:	15000 KG
Certificação:	ISO	Garantia:	1 ANO
Serviço After-sales ...	Suporte Online	Principais Pontos d...	Alta Produtividade
Após o Serviço de ...	Vídeo suporte técnico, Suporte Online, Peças de reposição	Localização Showr...	Nenhum
Indústrias aplicáveis:	Aviação, Automóveis, Trator, De Fabricação De Ferramentas	Local de Serviço Lo...	Nenhum
Capacidade Nomin...	3000KN		



Technical data

	GLO Annealing Furnaces, Retort made of 1.4841, Inconel or APM		
			
Model	GLO 40/11-1G	GLO 75/11-1G	GLO 120/11-1G
External dimensions			
***H x W x D* [mm]**	1900 x 1400 x 1800	2000 x 1600 x 1800	2100 x 1800 x 2000
Transport weight			
Complete system [kg]	1200	1500	2000
Usable space			
Volume [l]	40	75	120
***Ø x D* [mm]**	300 x 600	400 x 600	500 x 700
Thermal values			
T_{max}, vacuum [°C]	600 (1.4841)	600 (1.4841)	600 (1.4841)
T_{max}, atmospheric pressure [°C]	600 / 900 / 1100	600 / 900 / 1100	600 / 900 / 1100
ΔT, between 300 °C and 1100 °C [K] (according to DIN 17052)	± 3	± 3	± 5
Max. heat-up rate [K/min]	10	10	10
Cooling time [h]	7 – 9	7 – 9	8 – 10
Connecting values			
Power [kW]	25	40	60
Voltage [V]	400 (3P)	400 (3P)	400 (3P)
Current [A]	3 x 63	3 x 110	3 x 180
Series fuse [A]	3 x 80	3 x 160	3 x 200
Vacuum (option)			
Leakage rate (clean, cold and empty) [mbar l/s]	$< 5 \times 10^{-3}$		
Vacuum range depending on the pumping unit	rough, fine or high vacuum		
Cooling water required			
Flow [l/min]	1 – 3	1 – 3	1 – 3
Max. inlet temperature [°C]	23	23	23
Gas supply			
Nitrogen or Argon flow, others on request [l/h]	200 – 2000	200 – 2000	200 – 2000
Controller			
Manual operation	Eurotherm with KP 300 panel		
Automatic operation	Siemens		

Ver imagem maior

Super Máquina de moer de 5-aixs médio série s500x

FOB **Referência** Preço: Obter Cotação Imediata

100 000,00 US$ - 150 000,00 US$ / Jogo | 1 Jogo/jogos Depende do cliente exigência (Min. Ordem)

$50.00 DE DESCONTO Peça mais que $1,000.00 | Pegar cupom

Promoção para clientes novos
Até US$ 60 de desconto nas taxas de transação das 3 primeiras compras

Número do Mod... DJTOL S500X series

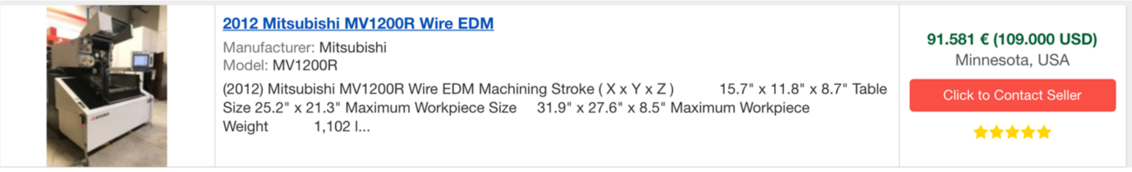
Garantia: **1 ANO** para o equipamento

Envio: Suporte Frete marítimo

Visão Geral

Detalhes Rápidos

Tipo:	Universal	CNC ou não:	CNC
Circunstância:	novo	Lugar de origem:	Anhui, China
Tensão:	220V	Dimensão (L*W*H):	2200*1800*2200 milímetros
Certificação:	ISO9001	Garantia:	1 ANO
Serviço After-sales ...	Suporte Online, Campo de instalação, comissionamento e trei...	Pós-o Serviço de v...	Engenheiros disponíveis para máquinas de serviço no exterior
Estado: novo:	Tipo: máquina de moer	Processamento: au...	Uso: geral
Nome do produto:	Ferramentas CNC máquina de moer S500X 5-aixs	Diâmetro de moed...	12mm
Comprimento de m...	160 milímetros	Poder (W):	16kw
Peso:	4500kg		

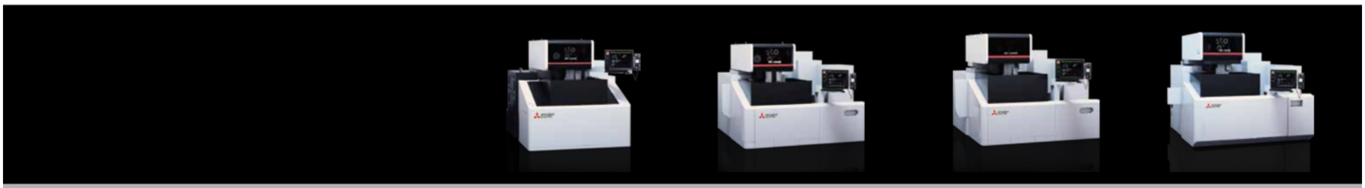


2012 Mitsubishi MV1200R Wire EDM

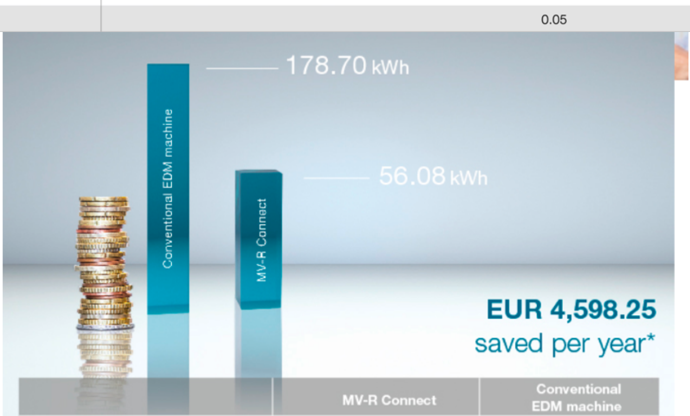
Manufacturer: Mitsubishi
Model: MV1200R

(2012) Mitsubishi MV1200R Wire EDM Machining Stroke (X x Y x Z) 15.7" x 11.8" x 8.7" Table Size 25.2" x 21.3" Maximum Workpiece Size 31.9" x 27.6" x 8.5" Maximum Workpiece Weight 1,102 l...

91.581 € (109.000 USD)
Minnesota, USA



Machine	MV1200R	MV2400R	MV2400R Z+	MV4800R
Travel (X/Y/Z) in mm	400/300/220	600/400/310	600/400/425	800/600/310
Travel (U/V) in mm	120/120 (+/- 60)	150/150 (+/- 75)	150/150 (+/- 75)	150/150 (+/- 75)
Taper angle (workpiece height) in °/mm	15/200 30/87	15/260 30/110	15/260 30/110	15/260 30/110
Max. workpiece dimensions (WxDxH) in mm	810x700x215	1050x820x305	1050x820x420	1250x1020x305
Max. workpiece weight in kg	500	1500	1500	3000
Table dimensions (WxD) in mm	640x540	840x640	840x640	1080x780
Table layout	Hardened 4-side frame table			Hardened 4-side table
Possible wire diameters in mm	0.1–0.3			0.15–0.3
Wire spool capacity in kg	10			10/16/20/25
Automatic wire threader/wire chopper	Yes/Yes			
Overall dimensions (WxDxH) in mm	2025x2760x2015	2687x3030x2150	2837x3452x2380	3100x3475x2415
Machine weight in kg	2700	3500	3650	5600
Mains voltage	3-phase 400 V/AC ± 10%, 50/60Hz, 13kVA			
Filter system				
Tank capacity in l	550	860	980	1480
Filter particle size in µm/filter elements	3/2			
Temperature control	Dielectric cooling unit			
Weight (dry) in kg	Included in machine weight	350	390	450
Generator				
Power supply unit	Regenerative transistor pulse type			
Cooling method	Fully sealed/indirect air cooling			
Max. output current in A	50			
Dimensions (WxDxH) in mm	600x650x1765			
Weight in kg	240			
Control				
Input method	Keyboard, USB flash drive, Ethernet, 19" touchscreen			
Control system	CNC, closed circuit			
Min. command step (X/Y/Z/U/V) in µm	0.1			
Min. axis resolution in µm	0.05			



EUR 4,598.25
saved per year*

	MV-R Connect	Conventional EDM machine
Time period (24 h day)		
Productive wire cutting	10h 32min	14h 06min
Stand-by	1h	9h 54min
Sleep Mode without wire cutting	12h 28min	–
Energy consumption in kWh		
Productive energy consumption	51.07	113.36
Energy consumption without wire cutting	2.69	65.34
Deactivating Sleep Mode	2.32	–

LENS® 850-R

Proven Industrial Additive Manufacturing System for Repair, Rework, Modification and Manufacturing

LENS 850-R is a state-of-the-art Additive Manufacturing system, using advanced alloys to restore the functionality of high value metal components.

LENS 850-R System

Impeller repaired by LENS 850-R System

The LENS 850-R system offers a large 900 x 1500 x 900mm working volume, making it ideal for repair, rework and modification of large industrial components. The LENS 850-R uses a high-power IPG Fiber Laser to build up structures one layer at a time directly from metal powder. The resulting material has mechanical properties that can be equivalent to or superior than the original component. The 850-R offers a full range of features, including 5-axis CNC-controlled motion, closed loop controls, and full atmosphere control. These features, backed by Optomec's full application and service support, make the 850-R the system of choice for industrial additive manufacturing users.

LENS FEATURES

- Large working volume - ideal for blisks, impellers and shafts
- 5-axis motion - rotary and complex repairs
- Closed-loop controls – precision process control
- Fiber Lasers – reduced cost of ownership
- Full software suite – generate toolpaths rapidly
- Full atmosphere control – superior material quality
- Common materials: Inconel Alloys, Stainless Steels, Titanium alloys

LENS APPLICATIONS

- Repair of worn components
- Rework of mis-machined components
- Modification of tooling for re-use
- Hybrid Manufacturing
- Advanced Product Development

OPTOMEC®
Production Grade 3D Printers... with a Material Difference
www.optomec.com

Optomec Inc.
3911 Singer Blvd. NE
Albuquerque, NM 87109 USA

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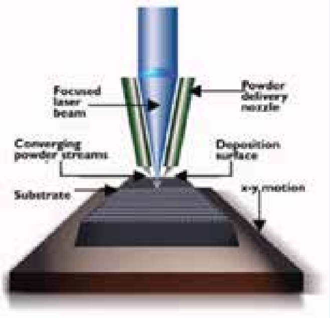
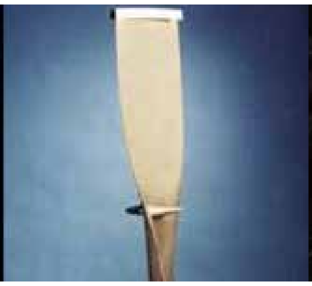
Laser Engineered Net Shaping



LENS® Deposition Head

How the LENS system works:
LENS systems utilize a high-power laser together with powdered metals to build fully dense structures directly from a 3-dimensional CAD solid model. The CAD model is automatically sliced into a tool-path, which instructs the LENS machine how to build the part. The part is constructed layer by layer under the control of software that monitors a variety of parameters to ensure geometric and mechanical integrity. The LENS process is housed in a chamber which is purged with argon such that the oxygen level stays below 10 parts per million to ensure there is no impurity pick-up during deposition. The metal powder is fed to the process by Optomec's proprietary powder-feed system, which is able to flow small quantities of powder very precisely. When complete, the part is removed and can be heat-treated, Hot-Isostatic Pressed, machined, or finished in any other manner.

Defense Housing
Fabricated by LENS/CNC Process



Compressor Blade
Repaired by LENS System

Exhaust Duct
Fabricated by LENS System

LENS 850-R Typical Performance Parameters

Process Work Envelope	900 x 1500 x 900 mm
Enclosure	Class I Laser Enclosure, Hermetically sealed to maintain process environment and Safety
Motion Control	5-axes standard: XYZ linear gantry motion Tilt-Rotate worktable All axes under full CNC control
Positional Accuracy	± .25mm
Linear Resolution	± .025 mm
Motion Velocity	60 mm/s
Deposition Rate	Up to 0.5 kg/hr
Parts Handling	Tilt-Rotate table tilts +/- 90°, infinite rotation. Rails and part cart allow table to move through machine and out. 38 cm diameter antechamber.
Gas Purification System	Dual unit maintains 02 level continuously ≤ 10 ppm
Powder Feeder	Two feeders each hold up to 14 kg of powder
Lasers	1 or 2 kW IPG Fiber Laser
Software	G-code Workstation Control; STL Editing; Part-Prep slicing
Closed-Loop Controls	Optional SMART-AM™ melt pool sensor
Enclosure Dimensions	3 x 3 x 3 m w/o gas purification system or laser

ABOUT OPTOMEC

Optomec® is a privately-held, rapidly growing supplier of Additive Manufacturing systems. Optomec's patented Aerosol Jet Systems for printed electronics and LENS 3D Printers for metal components are used by industry to reduce product cost and improve performance. Together, these unique printing solutions work with the broadest spectrum of functional materials, ranging from electronic inks to structural metals and even biological matter. Optomec has more than 200 marquee customers around the world, targeting production applications in the Electronics, Energy, Life Sciences and Aerospace industries. For more information about Optomec, visit http://optomec.com.

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Production Grade 3D Printers... with a Material Difference
www.optomec.com

Optomec Inc.
3911 Singer Blvd. NE
Albuquerque, NM 87109 USA

Tel: 505-761-8250
Fax: 505-761-6638
E-mail: requestinfo@optomec.com

1/2016