INSTITUTO SUPERIOR DE ENGENHARIA DO PORTO

MESTRADO EM ENGENHARIA MECÂNICA

COST ESTIMATION MODEL FOR THE DIRECTED ENERGY DEPOSITION PROCESS ADOPTING AN ACTIVITY-BASED APPROACH

JOÃO ABEL PASSOS DOS SANTOS

novembro de 2018

POLITÉCNICO
DO PORTO

COST ESTIMATION MODEL FOR THE DIRECTED ENERGY DEPOSITION PROCESS ADOPTING AN ACTIVITY-BASED APPROACH

João Abel Passos dos Santos

1120047

2018

Instituto Superior de Engenharia do Porto

Departamento de Engenharia Mecânica

POLITÉCNICO
DO PORTO

POLITÉCNICO
DO PORTO

Instituto Superior de Engenharia do Porto

COST ESTIMATION MODEL FOR THE DIRECTED ENERGY DEPOSITION PROCESS ADOPTING AN ACTIVITY-BASED APPROACH

João Abel Passos dos Santos

1120047

Dissertation presented to Instituto Superior de Engenharia do Porto in order to obtain the Master's Degree in Mechanical Engineering, performed under guidance of Prof. Eleonora Atzeni (Politecnico di Torino) and Prof. Francisco J. G. Silva (ISEP).

2018

Instituto Superior de Engenharia do Porto

Departamento de Engenharia Mecânica

POLITÉCNICO
DO PORTO

POLITÉCNICO
DO PORTO

JURY

Presidente

Prof. Manuel Jorge Dores de Castro

Professor Adjunto, Instituto Superior de Engenharia do Porto

Orientador

Prof. Francisco José Gomes da Silva

Professor Adjunto, Instituto Superior de Engenharia do Porto

Co-orientador

Prof. Eleonora Atzeni

Associate Professor, Politecnico di Torino

Arguente

Prof. António Paulo Monteiro Baptista

Professor Associado com Agregação, Faculdade de Engenharia da Universidade do Porto

ACKNOWLEDGMENTS

I would like to thank Prof. Eleonora Atzeni for giving me the opportunity to work under her advisement in Politecnico di Torino. I have learned a lot from and thanks to her. I am thankful for her guidance, patience and straight availability. Also, I thank to my co-supervisor, Prof. Alessandro Salmi, for all his support and all he has taught me. Thank you both for reviewing my thesis and for all the suggestions and advices. Finally, I express gratitude to my supervisor at ISEP, Prof. Francisco Silva for all the ideas, understanding and full support.

I would also like to thank my parents Abel and Margarida, as well as my sister Sofia, for all the support and assistance given throughout my academic career and especially in my life. Without them, none of my achievements would be possible.

ABSTRACT

Additive Manufacturing (AM) is a manufacturing process capable to produce three-dimensional components and products directly from raw material and 3D design data. This layer-by-layer operating process has many advantages, including high geometrical freedom and short lead time, enabling the production of single parts or small series with reduced costs, compared to conventional processes.

One of the metal AM processes, which is, currently, receiving a lot of attention is the Directed Energy Deposition (DED). This technology is an effective manufacturing technique to build metallic and functional parts and to repair valuable components. DED uses a high-powered laser as a focused heat source to locally melt the delivered powder or wire-shaped raw materials. In this process, the delivery of powder can be carried out by using either a single nozzle or multi-nozzle configuration of the deposition head. Different technologies are usually labeled as DED processes, such as the Laser Engineering Net Shaping (LENS), which is a common technology of deposition with multi-nozzle.

The aim of this study is to perform technological and economic assessments of a Directed Energy Deposition process by developing a cost estimation model which evaluates and estimates the process costs along the DED process chain. Cost is generally the key point for decision making, with break-even points for different manufacturing technologies being the dominant information for decision-makers. Cost estimation may be also profitable for designers and engineers at the preliminary design stage to understand the cost impact of alternative designs. In this study, the main cost elements are defined and discussed along the process chain, in addition to being also considered sustainability issues related with the DED process.

KEYWORDS

Additive Manufacturing, Directed Energy Deposition, Manufacturing Costs

RESUMO

O Fabrico Aditivo é um processo de fabrico capaz de produzir peças e componentes tridimensionais diretamente a partir do material usado como matéria prima e com base nos dados da sua geometria em CAD 3D. Este processo de deposição, camada por camada, possui inúmeras vantagens, como por exemplo grande flexibilidade e capacidade de liberdade geométrica com tempos curtos de preparação, possibilitando a produção de peças individuais ou de baixas séries de produção a custos reduzidos, quando comparado com os processos ditos convencionais.

Um dos processos de Fabrico Aditivo de metais mais promissores é o *Directed Energy Deposition* (DED). Esta tecnologia não só permite construir peças metálicas e funcionais de forma eficiente, como também possibilita a reparação de componentes complexos ou de alto valor. O DED usa um laser de alta potência como fonte de energia para fundir a matéria-prima que pode estar em forma de pó ou fio. Neste processo o fornecimento da matéria-prima em forma de pó pode ser realizado através de um só bocal ou de vários bocais que fazem a deposição do material. Existem diferentes variantes do processo DED sendo a mais conhecida a *Laser Engineering Net Shaping* (LENS), que utiliza vários bocais como meio de deposição.

O objetivo deste trabalho é desenvolver uma análise económica e tecnológica do processo DED através da realização de um modelo de estimativa de custos capaz de avaliar e prever os montantes envolvidos em toda a sua cadeia de processo. O custo é geralmente um ponto chave para a tomada de decisões, de modo a obter-se o melhor compromisso entre as várias possibilidades de tecnologias de processamento a usar. A estimativa de custos pode ser também vantajosa para os engenheiros e elementos do grupo de projeto numa fase preliminar da conceção de um novo produto, de modo a melhor poder decidir o impacto económico de conceções alternativas. Neste trabalho são determinados e examinados os principais custos ao longo da cadeia do processo DED, incluindo e tendo em consideração os aspetos de sustentabilidade ambiental deste processo.

PALAVRAS-CHAVE

Additive Manufacturing, Directed Energy Deposition, Custos de fabrico

CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ACRONYMS

3DP	Three-Dimensional Printing
AM	Additive Manufacturing
AMF	Additive Manufacturing File Format
ASTM	American Society for Testing and Materials
CAD	Computer-Aided Design
DED	Directed Energy Deposition
DMD	Direct Metal Deposition
DMLM	Direct Metal Laser Melting
DMLS	Direct Metal Laser Sintering
EBAM	Electron Beam Additive Manufacturing
EBM	Electron Beam Melting
FDM	Fused Metal Deposition
FLM	Fused Layer Modeling
ISO	International Organization for Standardization
LBAM	Laser-Based Additive Manufacturing
LENS	Laser Engineered Net Shaping
LMD	Laser Metal Deposition
LOM	Laminated Object Manufacturing
MJM	Material Jetting Modeling
Nd:YAG	Neodymium-doped yttrium aluminum garnet
PBF	Powder Bed Fusion

SLA	Stereolithography
SLM	Selective Laser Melting
SLS	Selective Laser Sintering
STL	Standard Tessellation Language
USD	US dollars
UV	Ultraviolet

INTRODUCTION

1 INTRODUCTION

1.1 Overview

Nowadays, high competition, globalization and a shift towards the buyers' market are some of the main challenges faced by the manufacturing industry. In this modern manufacturing environment, effective and flexible manufacturing technologies are the foundation for success in everyday businesses. Buyers seek innovative, customized and high-quality products but they refuse to pay higher prices at the same time. Additionally, the economic lifespan of these products decreases with the tendency of shorter time-to-market and shorter development cycles. Furthermore, the individualization of customer demands increases along with the increase of different variants. One possibility to meet with these tendencies may be delivered by technologies of AM-Additive Manufacturing [1, 2].

AM technologies enable the deposition of material, layer-by-layer, to create any object from three-dimensional (3D) model data. Commonly known as 3D printing, AM offers many advantages when compared to other manufacturing processes: parts can be easily produced on-demand with customization and personalization, no special tooling is required for part fabrication, material waste is greatly reduced, the time and cost of manufacturing can be reduced significantly for single parts and small-quantity productions, new components and structures with complex geometries and heterogeneous compositions can be fabricated without difficulty using AM technologies and also the supply chain is compressed radically [3].

According to the International Organization for Standardization (ISO)/American Society for Testing and Materials (ASTM) 52900:2015 standard, AM processes are classified into seven categories: Vat Photopolymerisation, Material Jetting, Binder Jetting, Material Extrusion, Powder Bed Fusion, Sheet Lamination, Directed Energy Deposition [4, 5]. Nowadays, Directed Energy Deposition is noticeably emerging and revealing great capabilities within the metallic AM technologies. This AM technique, which uses focused thermal energy to fuse materials by melting along with its deposition, has shown a significant growth in the last decade and this can be deduced from the noteworthy number of publications and researchers or institutes concentrating on this topic [6]. However, the literature that can be currently found on DED technologies still does not include a cost model which evaluates and quantifies the cost effectiveness of DED, being this aspect the main motivation for the prosecution of this thesis work.

1.2 Main Goals

The main goal of this work is to analyze the cost-effectiveness of a Directed Energy Deposition (DED) process. Thus, in order to find answers for this issue, the following objectives have been defined:

- to understand the mechanism of the DED process and examine all the processing steps;
- to analyze and determine all the costs along the DED process chain;
- to perform a cost estimation model which evaluates and estimates the costs;
- to figure out how profitable is the DED process among other comparable techniques.

1.3 Methodology

The methodology adopted to accomplish this work was based on the following procedures:

- to study and write about the general topic: Additive Manufacturing;
- to investigate about the literature of the DED process, in order to make the Theoretical Review;
- to analyze and comprehend all the costs regarding the DED process;
- to develop and test methodologies and cost calculations, associated with the process;
- to inquire and discuss about some cost elements of a DED process in cooperation with Italian company “Prima Industrie” which is adopting the DED technology;
- to implement the cost estimation model in an excel spreadsheet considering the costs and identified calculations;
- to analyze and discuss the results obtained using the necessary graphs and charts;
- to perform a sensitivity analysis and discussing results;
- to compare the results with those reported in literature on metallic AM;
- to write the conclusions and define directions for future work.

1.4 Thesis Structure

This work is divided into four chapters.

Chapter 1 presents an introduction on the topic of this work, the main goals, the adopted methodology and also the structure of this dissertation.

Chapter 2 consists in a detailed review of relevant studies, which represent the fundaments to frame this work. In the theoretical review, an introduction to the Additive Manufacturing (AM) process is made, including AM processing steps, history, standardization, techniques, applications, industrial involvement, advantages and disadvantages, as well as costs. Also, a review on Directed Energy Deposition (DED) is made, in which the description and mechanisms are mentioned, along with producers and applications of DED process.

In chapter 3, a study and analysis is performed about all the costs concerned within a DED technology in addition to an explanation of corresponding calculations and formulas needed to implement the cost estimation model. Furthermore, the results obtained from the cost model are evaluated and broken down and they are also compared with the published data from the literature.

Finally, chapter 4 presents the conclusions from current work and suggests future directions for further research in this topic.

THEORETICAL REVIEW

2 THEORETICAL REVIEW

2.1 Additive Manufacturing (AM)

2.1.1 Introduction

Additive manufacturing (AM) is defined, according to ASTM, as "a process of joining materials to make parts from three-dimensional (3D) model data, usually layer upon layer, as opposed to subtractive manufacturing and formative manufacturing methodologies" [7, 8]. The process was initially mentioned as rapid prototyping and rapid manufacturing. Currently, it can also be referred as 3D printing, additive fabrication, additive process, additive techniques, additive layer manufacturing, layer manufacturing and freeform fabrication [5].

This feature of translating virtual solid model data into physical models in an efficient process, allowing production of complex and customized parts directly from the design without the need for expensive tooling or forms such as punches, dies or casting molds and reducing the need for many conventional processing steps [9]. Traditional machining produces the part from stock by removing the material, in a way that scrap and rework are inherent to these processes. In AM, the parts are directly manufactured on the AM machine, reducing scrap and rework, as represented in Figure 1 [10]. For this reason, AM can be a profitable alternative to conventional manufacturing processes such as casting, welding, machining and molding.

In this process, the model data initially generated using a 3D Computer Aided Design (CAD) system is broken down into a series of two-dimensional cross-sections of a finite thickness. These sections are fed into AM machines by combining and adding them together in a layer-by-layer sequence to form the physical part. Therefore, the AM can be considered a "What You See Is What You Build" (WYSIWYB) process which is notably valuable when more complexity is associated with the geometry [11].

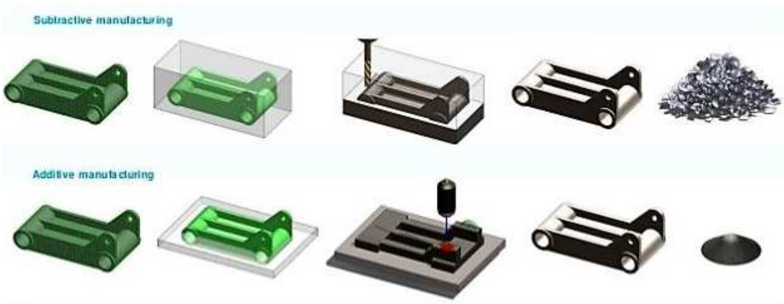


Figure 1 - Additive manufacturing vs. subtractive manufacturing.

2.1.2 AM Processing Steps

The AM process requires a few steps which difficulty varies depending on the complexity of the object to be produced.

In broad terms, the process begins with a 3D model of the object created by a CAD software or a scan of an existing artifact. Then, specialized software slices this model into cross-sectional layers, creating a computer file that generates instructions to be sent to the AM machine. The machine then creates the object by forming each layer via the selective placement (or forming) of material [12]. After the building process is complete, the parts may get ahead to the stage of finishing whereupon there are careful cleaning and post-processing.

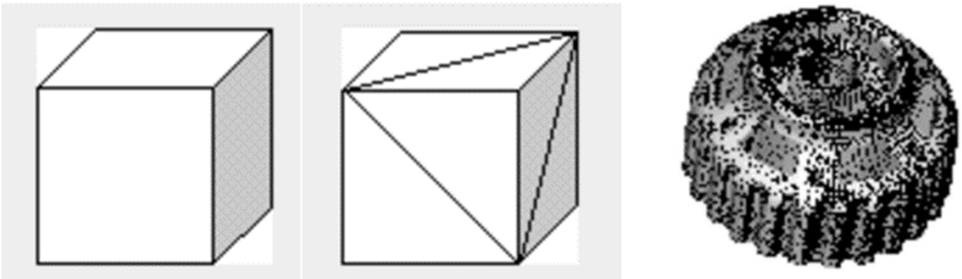
The generalized stages of AM technologies shown in Figure 2, are detailed in the following paragraphs.

Figure 2 - Generalized AM process [13].

2.1.2.1 Modelling

The AM process must start with a 3D model, that fully describes the external and internal geometry of the object, created by a CAD software. This CAD file is then converted into a language that AM machines can understand [11]. Standard Tessellation Language (STL) is the most commonly used file format, where the surfaces of the model are discretized by triangles, respecting a given tolerance. Although other file formats have been developed and standardized to support AM data preparation and digital workflow such as the Additive Manufacturing File Format (AMF), which has native support for color, materials, lattices and constellations. Thompson et al. [14] stated this file format is intended to replace the STL format. Due to its multi-material capability and efficiency to handle material related information, the AMF can overcome CAD and digitalization constraints [14].

Concerning the STL file conversion, for a simple model such as a quadrangular box, its surfaces can be approximated with twelve triangles, as presented in Figure 3 (a). The more complex the surface, the more triangles are produced. As shown in Figure 3 (b), due to the model complexity, the surfaces are approximated to many triangles [15].



(a) (b)

Figure 3 - (a) Simple CAD model (3DSystems 2018); (b) More complex CAD model [15].

The STL file may require some corrections, so that it contains the correct size, position, scale and orientation for building [11]. For this reason, there are STL editor software's (e.g. Materialise Magics) that allow file conversion to STL, editing the design, preparing the build platform and fixing errors, such as inverted normals, bad edges, holes and sharp, double or overlapping triangles [16]. This file describes the external and internal closed surfaces of the original CAD model and forms the basis for calculation of the slices. The specialized software slices the model into cross-sectional layers from the STL file, creating a computer file that is sent to the AM machine – the SLI file [11].

At this point, there are also other aspects to be concerned with, such as the part orientation and the support structures. The first one influences the surface quality and the possibility to build certain geometries due to limitations like gravitational forces or need for support structures. The adoption of the most efficient part orientation can reduce the need of support structures. They may be reduced in order to minimize the removal time, the scrap and to improve the surface quality. Nevertheless, these structures can be necessary to either help and/or overcome gravitational forces, as well as to remove heat generated and consequent stress concentration, and to hold the part, thus preventing warping effect [7].

2.1.2.2 Building

The main point of the process is building the part. After the converted file is transferred to the AM machine, the part can start being produced. Firstly, the operator should set-up the machine by preparing the raw material and the process parameters. Thereafter, the process is mainly an automated operation and the machine can largely carry on the processing, without supervision. Only trivial monitoring of the machine is necessary at this moment to ensure no errors have taken place like running out of material, power or software glitches. Moreover, the parts may need additional cleaning and arrangement. Also, they may have support structures that must be removed [11].

2.1.2.3 Finishing

The finishing stage should be the last stage before the part is ready for its application. Concerning the surface finish, AM is today a process that usually does not deliver mirror-like flat surfaces. Instead, the surface roughness and tolerances should be comparable to an investment cast part, see Figure 4 [17].

In this ultimate stage of the process, depending on the case, the parts may also undergo heat treatments, thermal stress relieving treatments, ultraviolet light curing, machining operations, sandpapering, polishing, coatings' applications and final inspections [7, 17, 18].

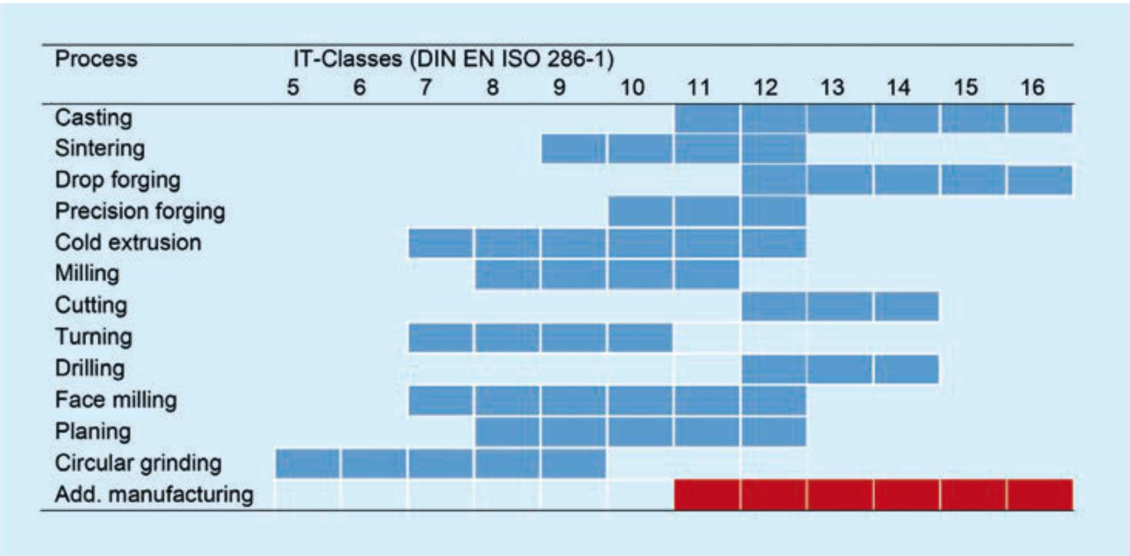


Figure 4 – Comparison of surface tolerances for different manufacturing processes [17].

2.1.3 History

The concept of Additive Manufacturing, originally titled as Rapid Prototyping, has been researched and developed, especially in the last three to four decades. It was in the 1980s that AM started being used for commercial purposes [5, 19]. Following this trend, in 1987 the company 3D Systems, in USA, created the first available commercial AM system and the pioneering process was Stereolithography (SLA), a process that solidifies thin layers of ultraviolet (UV) light-sensitive liquid polymer using a laser [19]. Since then, many companies performed important research and made impressive developments in order to improve the process and develop new technologies and commercialize them both in Europe, as example the Selective Laser Sintering (SLS) by EOS (Electro Optical Systems), and in Japan with the company NTT [20]. Also, researchers in the domains of mechanical engineering and materials science have focused on improving old and creating new AM methods, as well as developing novel materials [12]. Over all this period, AM has been slowly gaining traction, essentially within the product design, as represented in Figure 5 [13].

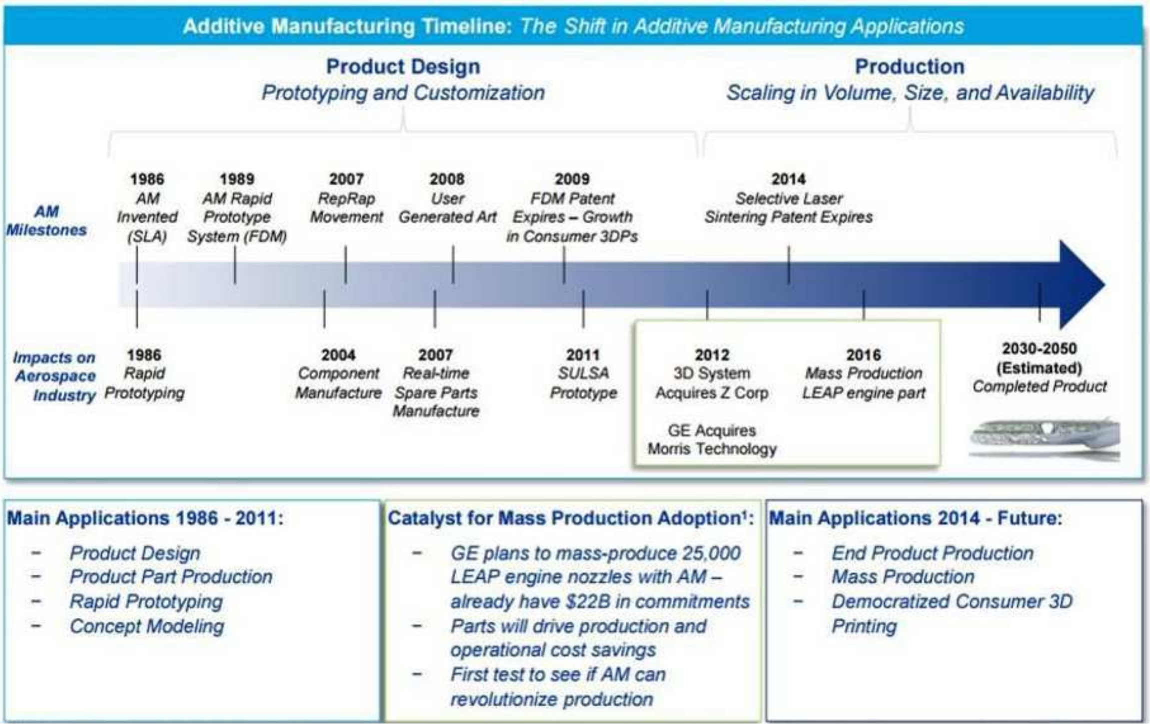


Figure 5 - AM important milestones [13].

With the proliferation of computer graphics and CAD, better materials, improved process reliability and global interaction promoted by Internet, AM took off exponentially in the mid 2000's, as noticed in Figure 6. The main factors propelling this exponential growth are the range of materials and accessibility. Until the mid 2000's, AM was possible only with soft plastic, severely limiting its main application field - rapid prototyping. Since then, the range of materials has increased dramatically, making it possible to create high-resolution, strong and functional products, which are ready for end-use. This manufacturing process is currently applied across various fields including aerospace, automotive, electronics, medical and education. It is revolutionizing many fields and disciplines, demonstrating that almost every industry could benefit to some extent from this technology, with full potential to amplify growth and extend its usage within mass production [13, 21].

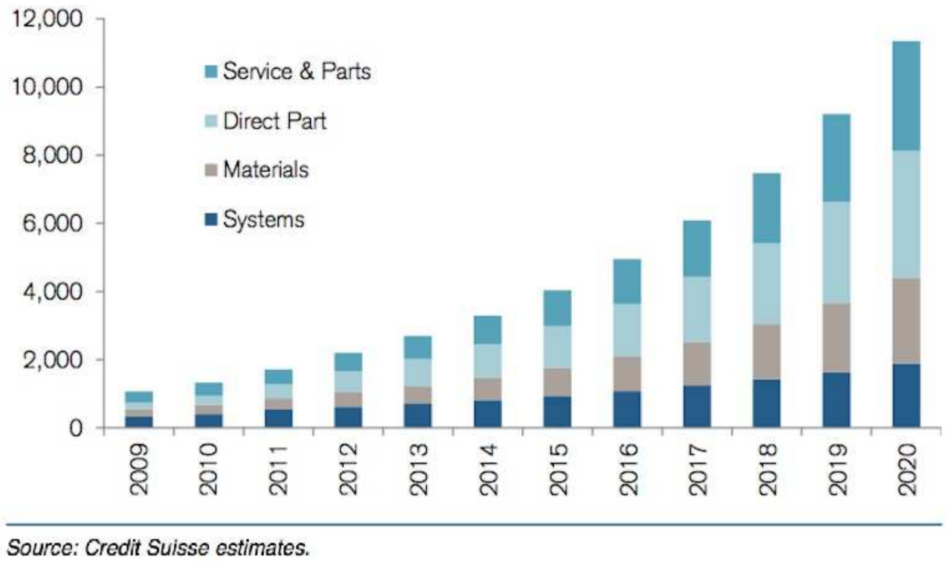


Figure 6 - Primary global AM market growth (US dollars in millions) [22].

Nowadays, a myriad of AM technologies is rapidly evolving, creating new opportunities to disrupt business models in many industries. To highlight this development, the hype cycle (see Figure 7) has been shown by Gartner firm, an information technology (IT) research and consultancy company. This branded tool illustrates how a technology proceeds through a series of particular “expectation levels”, as it matures [23]. It identifies five overlapping stages in a technology’s life cycle: Innovation Trigger, Peak of Inflated Expectations, Through of Disillusionment, Slope of Enlightenment and Plateau of Productivity [24].

Along these lines and considering the hype cycle of AM (Figure 7), it is possible to see that technologies like 4D Printing, Nanoscale 3DP, 3D-Printed Drugs and 3D Bio-printed Organ Transplants are on the rise. Some examples of those at the “peak” are Powder Bed Fusion, Directed Energy Deposition and 3D Printed Surgical Implants. Those sliding into the “through of disillusionment” are, for instance, 3DP of Medical Devices, 3DP in Aerospace and Defense and Stereolithography. As for those climbing the “slope of enlightenment”, one may find 3DP of Dental Devices, 3DP in Automotive or Enterprise 3D Printing. Finally, in the last stage, 3DP for Prototyping and 3DP of Hearing Devices are entering the “plateau of productivity” [24].

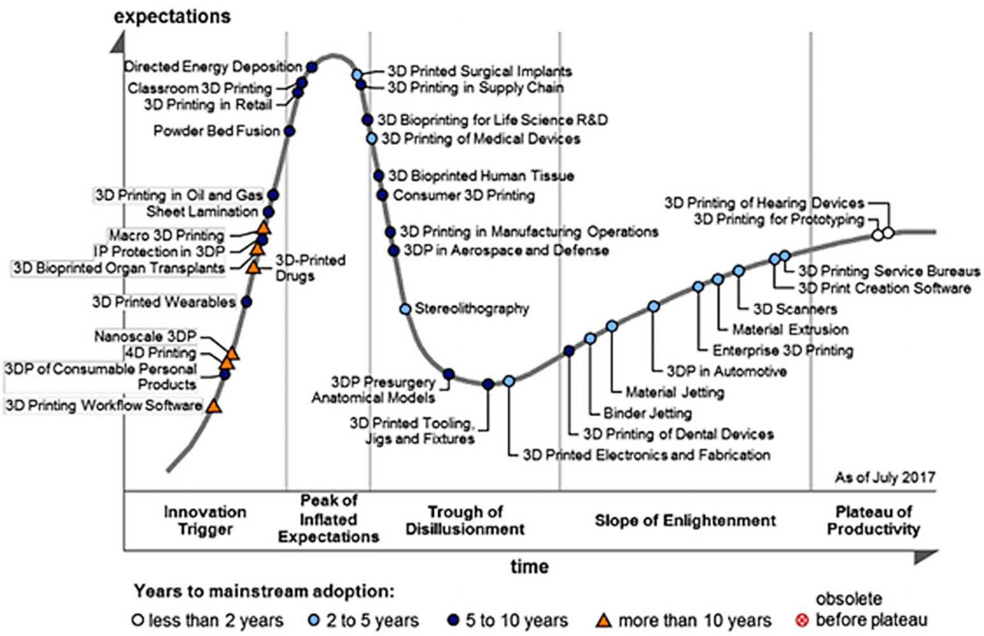


Figure 7 – The Gartner hype cycle diagram [23].

2.1.4 ASTM F42 and Standardization

Numerous AM technologies are presently available and have been introduced to the market by several industrial companies, including Electro Optical Systems (EOS) in Germany, MTT Technologies Group in England, Arcam in Sweden and Optomec, Stratasys, 3D Systems and Z Corp in the United States, among others [25].

In 2010, the American Society for Testing and Materials (ASTM) group "ASTM F42 – Additive Manufacturing", formulated a set of standards classifying the range of Additive Manufacturing processes into seven categories [4]. Accordingly, the following categories are considered: Vat Photopolymerisation, Material Jetting, Binder Jetting, Material Extrusion, Powder Bed Fusion, Sheet Lamination, Directed Energy Deposition [4, 5]. Table 1 shows these major technologies, as well as, the corresponding deposition materials and commercial machine suppliers.

Table 1 - ASTM categorization [5, 26].

Process Category	Process	Materials	Manufacturers
Vat Photopolymerization	Stereolithography (SLA)	UV curable resins	Asiga 3D Systems EnvisionTEC Rapidshape
		Waxes	DWS
		Ceramics	Lithoz
Material Jetting	Polyjet/Projet	UV curable resins	3D Systems Stratasys
		Waxes	Solidscape
Binder Jetting	3D Printing (3DP)	Composites	3D Systems
		Polymers, Ceramics	Voxeljet
		Metals	ExOne
Material Extrusion	Fused Deposition Modeling (FDM)	Polymers	Stratasys MakerBot RepRap Bits form Bytes Fabbster Delta Micro Factory Corporation Beijing Tiertime
		Waxes	ChocEdge Essential Dynamics Fab@Home
Powder Bed Fusion	Selective Laser Sintering (SLS)	Polymers	EOS Blueprinter 3D Systems
		Metals	3Geometry Matsuura 3D Systems
	Selective Laser Melting (SLM)	Metals	EOS SLM Solutions Concept Laser 3D Systems Realizer Renishaw
	Electron Beam Melting (EBM)	Metals	Arcam Sciaky
Sheet Lamination	Laminated Object Manufacturing (LOM)	Paper	Mcor Technologies
		Metals	Fabrisonic
		Polymers	Solido
Directed Energy Deposition	Laser Metal Deposition (LMD)	Metals	Optomec DM3D Irepa Laser
	Electron Beam Direct Melting (EBM)	Metals	Sciaky

For each technology, a single manufacturer may have different machines that differ from each other in terms of build envelope and process parameters, such as manufacturing speed or layer thickness and cost [26].

Other methods to classify AM processes may be found. An example is the division into four broad categories based on the state of starting material: liquid, filament/paste, powder and solid sheet [27, 28]. Another example is to categorize AM processes based on the types of part materials, such as polymers, metals, ceramics, composites and biological materials [26].

As of February 2017, fourteen AM industry standards have been published by the international organization American Society for Testing and Materials (ASTM). The standard ISO/ASTM 52900-15 “Standard terminology for additive manufacturing technologies” sets the terminology, including process definitions and other terms associated with the industry. Process definitions and terms from this standard were fully adopted in 2012. The ISO/ASTM 52921-13 “Standard terminology for additive manufacturing - Coordinate systems and test methodologies” defines terminology for coordinate systems and testing methodologies. The ISO/ASTM52915-16 “Standard Specification for Additive Manufacturing File Format (AMF)” defines the AMF file format, which serves as an alternative to the STL file format. The ISO/ASTM 52910 is the guide for Design for AM. The standard ASTM F2971-13 “Standard practice for reporting data for test specimens prepared by additive manufacturing” defines the level of data to be recorded when producing additively manufactured specimens for record. The F3122-14 “Standard guide for evaluating mechanical properties of metal materials made via additive manufacturing processes" determines a number of current standards to be considered when evaluating additive manufactured products. The F2924-14 "Standard specification for additive manufacturing titanium-6 aluminum-4 vanadium with powder bed fusion” helps producers and purchasers of Ti-6Al-4V parts using the powder bed fusion process to define requirements and to ensure consistent part properties. The F3001-14 standard is the “Standard specification for additive manufacturing titanium-6 aluminum-4 vanadium ELI (extra low interstitial) with powder bed fusion”. The F3049-14 standard is the standard guide for characterizing properties of metal powders used for AM processes. The F3091/F3091M-14 standard is the standard specification for powder bed fusion of plastic materials. The F3055 standard "New specification for additive manufacturing nickel alloy (UNS N07718) with powder bed fusion” helps producers and users of additively manufactured nickel UNS N07718 parts to define requirements and ensure consistent part properties. The F3056 standard “Specification for additive manufacturing nickel alloy (UNS N06625) with powder bed fusion” covers additively manufactured nickel alloy UNS N06625 parts using full melt powder bed fusion such as electron beam melting and laser melting. The F3184-16 standard is the standard specification for AM stainless steel alloy (UNS S31603) with powder bed fusion. The F3187-16 standard is the standard guide for directed energy deposition of metals [19].

2.1.5 AM Processes

As its name indicates, Additive Manufacturing comprehends the process that adds material during a part manufacturing. The categories presented here are briefly described, as well as some of the main corresponding technologies and they are those regulated and standardized by ASTM.

2.1.5.1 Vat Photopolymerization

The oldest of the commercial AM processes makes use of liquid, radiation curable resins (photopolymers) as primary materials. Most photopolymers react to ultraviolet radiation, but others are cured even by visible light wavelength radiation [11].

About the product obtained, edges curl upwards and other distortions of the part can occur due to volumetric shrinking, which happen when the photopolymer is exposed to the UV light and solidifies, inducing compression stresses on previous layers. Parts produced using low molecular weight resins, such as polyacrylate or epoxy macromeres, were primarily glassy, rigid and brittle. To improve the mechanical behavior of the parts, epoxy-based and hybrid polymers (epoxides with some acrylate content) are also employed. In this way, the quality of the built part is increased, because such materials are more insensitive to humidity and shrinkage. This type of process frequently requires support structures which adversely affect the surface quality touched by them, inducing, as well, long and labor-intensive post-processing operations. The parts can be further processed by finishing operations to improve the aesthetic appearance. Thus, parts can be sanded to eliminate the support marks and then painted [5].

Vat Photopolymerization is applied in several industries, including the aerospace sector, to produce functional components in a cost-effective and quick manner, as well as in the automotive sector to create prototypes for automotive design verification and functional testing. Complex functional electronic and electromechanical systems can be produced by this AM technology. The biomedical applications are numerous. The most widespread clinical application in dentistry has been the fabrication of surgical templates to assist in dental implant planning and for the production of maxillary/mandibular prosthesis. In chemical engineering field it is also applied for the production of micro-transducers, micro-pumps, in micro-fluidic applications or micro heat-exchangers with internal channels dimensions of millimeters [5].

Stereolithography (SLA): In this process, the resin is contained in a vat, allowing just one liquid layer over the support surface. The depositing process consists on a UV laser source and a scanner system, composed by a set of mirrors, projecting the laser beam in a point wise fashion over the resin layer, which is cured when exposed. The scanning over the layer follows a hatching pattern which is repeated in the further layers after completion of each layer and lowering of the support platform by one thickness step. Two other SLA configurations are Mask Projection and Two-photon [5].

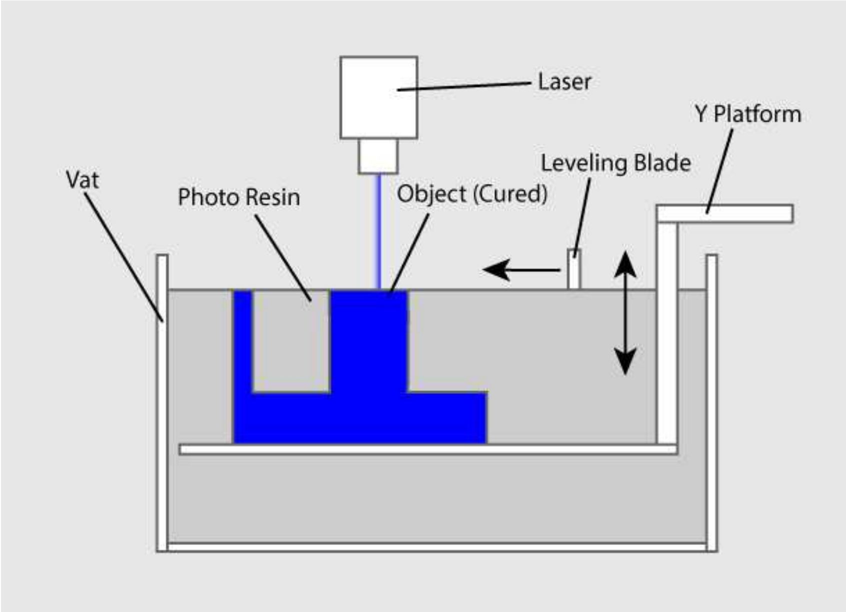


Figure 8 - Schematic of Stereolithography process [29].

2.1.5.2 *Material Jetting*

In Material Jetting process, 3D models are made by selectively depositing droplets of material onto a build platform, as illustrated in Figure 9. Generally, current commercial material jetting technologies use photosensitive thermoset polymers which are cured upon deposition. This builds upon well-established inkjet technologies developed for conventional two-dimensional printing [30].

Regarding the part created, different properties and characteristics can be obtained by depositing materials of different colors and hardness in the same part. The material-jetting printers can produce parts with resolution in the range of 10-30 μm, making the layers barely noticeable [5].

The main commercial applications for this process remain in graphics, product marking, coding and dating. In recent years, there has been considerable interest in technological areas, such as aerospace and defense, architecture, commercial products, consumer products, automotive, medical, entertainment and sports [5].

Polyjet/Projet: This is a material jetting technology producing smooth, accurate parts, prototypes and tooling made of multiple materials. Parts with different mechanical and physical properties, durable surfaces and exceptionally fine details can be manufactured, all in a single build. With microscopic layer resolution and accuracy down to 0.1 mm, it can produce thin walls and complex geometries using the widest range of materials available. The Polyjet and Projet systems can print living hinges, soft-touch and overmolded parts, not possible with other technologies. Polyjet and Projet are branded technologies from Stratasys and 3DSystems [21].

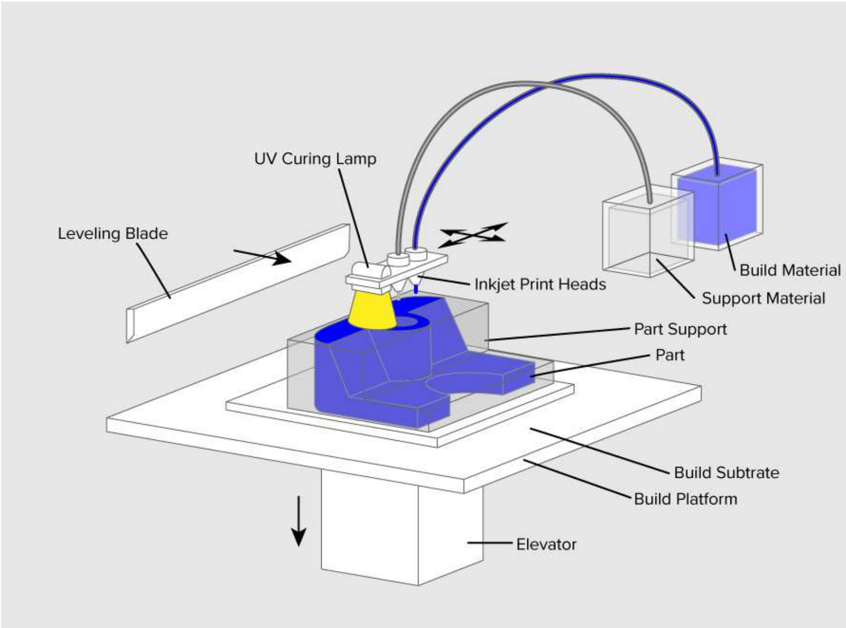


Figure 9 - Schematic of Material Jetting process [29].

2.1.5.3 *Binder Jetting*

Binder Jetting is a sort of processes in which a liquid bonding agent is selectively deposited in the form of droplets to join powder materials (see Figure 10). Often, the binder has adhesive properties and it is ink-jetted onto the surface of a powder bed. Production of structural materials typically requires some operations of post-processing to remove the binder and to densify the constituent powder [30].

The combination of powder materials and additives in binders enables material compositions that are not easily possible using direct printing methods. The parts fabricated using binder jetting processes tend to have poorer dimensional accuracy and meaner surface finish than parts made with direct printing. Infiltration steps are needed to fabricate dense parts or to ensure good mechanical properties [11].

Binder Jetting is widely used to print sand molds for castings or to generate complex ceramic parts. These custom ceramic structures possess significant potentials in many applications, such as dentistry and aerospace, where extreme environments are present. Specifically, highly customized geometries with adequate performance are needed for various dental prostheses applications [31, 32].

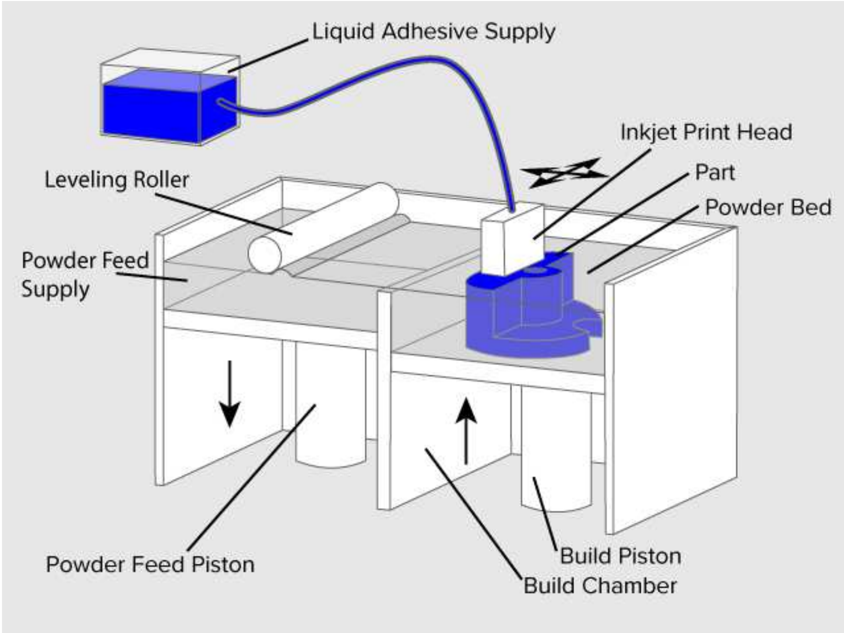


Figure 10 - Schematic of Binder Jetting Process [29].

Tridimensional Printing (3DP): This is a technology in which the material is deposited by a printer head or nozzle. In 3DP, models are built from a powder material (which can be a blend using materials like composite cellulose among others), infiltrated with a liquid binder. This binder is applied through the printer head as used in traditional printing. The part is removed having the dust blended with the binder and needing operations of cleaning and medium consolidation [18, 33].

2.1.5.4 Material Extrusion

These deposition processes may also be considered liquid processes, since they are based on melting of a thin plastic filament and its extrusion is performed through a nozzle of a scanning head, as schematically represented in Figure 11. The scanning head draws transversal section perimeters and fills them, building in this way each layer. Common filament materials are polycarbonate (PC) and acrylonitrile butadiene styrene (ABS), which is the most used due to its good mechanical properties [33]. The biodegradable plastic Polylactic Acid (PLA) can also be used as raw material [30]. AM material extrusion is also known as Fused Layer Modeling (FLM). Fused Deposition Modeling (FDM) is a Stratasys registered trade name for FLM [18].

The surface roughness of manufactured parts is deeply affected by the layer height of the prototypes, depending also on the shape of the part and surface curvature with respect to the building orientation. This parameter could be maintained at its lower value, so that better roughness values are obtained. Also, the quality of the parts depends on the building orientation, on the layer thickness and on the feature size. The parts can be polished to improve the smoothness of the part surface, whether it is painted or metal plated. Unconventional finishing processes might also be employed to improve the superficial finishing [5].

A broad range of applications in different sectors are associated with this process. However, it is in aerospace manufacturing applications that this process is the most promising, representing also a sustainable additive technology. The use of a solid filament is an advantage in a vacuum or microgravity environment, where powder beds or liquids cannot be used as raw materials [5].

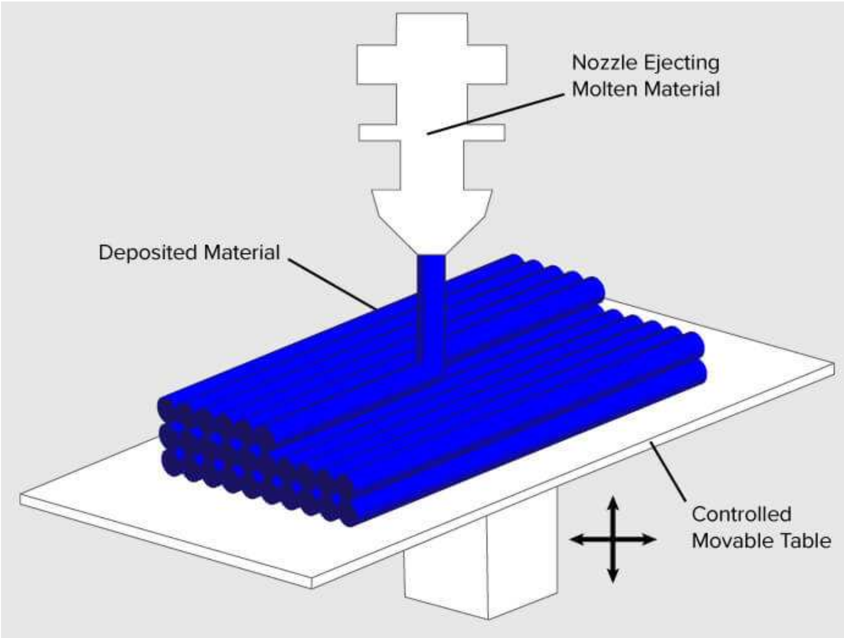


Figure 11 - Schematic of a Material Extrusion process [29].

2.1.5.5 Powder Bed Fusion (PBF)

In Powder Bed Fusion processes, a powder is either fused or sintered by a carbon dioxide laser beam. To operate with a lower laser power, the machine chamber containing the powder is heated near to the material melting point, which fuses with a small temperature differential. The chamber is also flooded with a shielding gas to prevent oxidation. After part completion, it needs cooling down and cleaning up for powder removal [18, 30].

There are two main variants of this category: Selective Laser Melting (SLM) and Electron Beam Melting (EBM).

Virtually, any material that can be powdered, such as plastic, polymer, ceramic, metals and even composites can be fused, employing these AM technologies. This process demands a post-processing work, in order to obtain a better surface finish [33, 34].

Powder bed fusion, due to minimal constraints on feedstock type for manufacturing, is popular for part manufacture for service applications. In the case of Selective Laser Melting, there are wide applications in marine, in aerospace sector (e.g. turbine engines, high-speed airframe parts, high-temperature bolts and fasteners), automotive sector (e.g. fuel cells) and in biomedical industry (e.g. dental restorations and orthopedic implants). Regarding the industrial market of Electron Beam Melting, two main fields should be pointed out: aerospace and orthopedic implants. With regard to orthopedic implants, EBM is used to produce parts, such as acetabular cups, knee, maxillofacial plates, hip, jaw replacements, etc. [5, 30].

Selective Laser Melting (SLM)/Electron Beam Melting (EBM): These are processes in which thermal energy is used to locally fully melt regions of a powder bed. The materials used are usually metals like plain steel, titanium, aluminum and nickel alloys [30]. With respect to SLS, the equipment differences include a fiber laser beam and different shielding gases. EBM is an AM powder based process where an electron beam is used instead of the laser [18]. An illustration of SLM and EBM can be observed in Figure 12 and Figure 13, respectively.

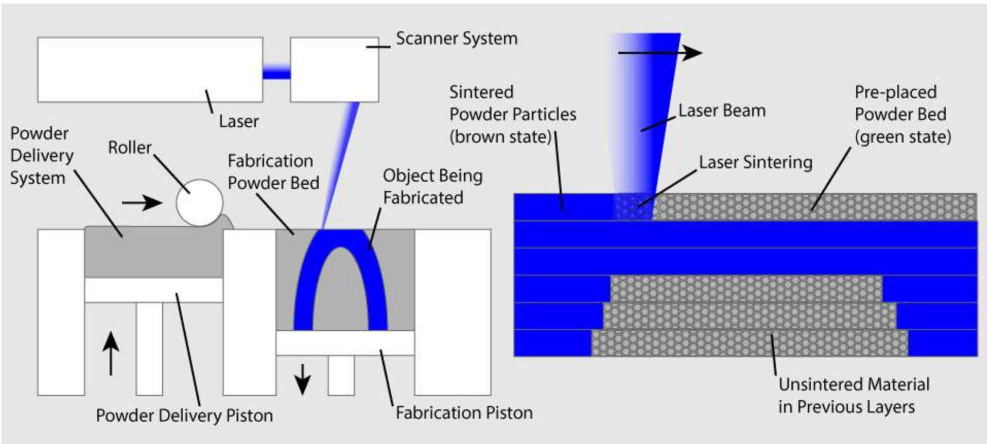


Figure 12 - Schematic of Selective Laser Melting process [29].

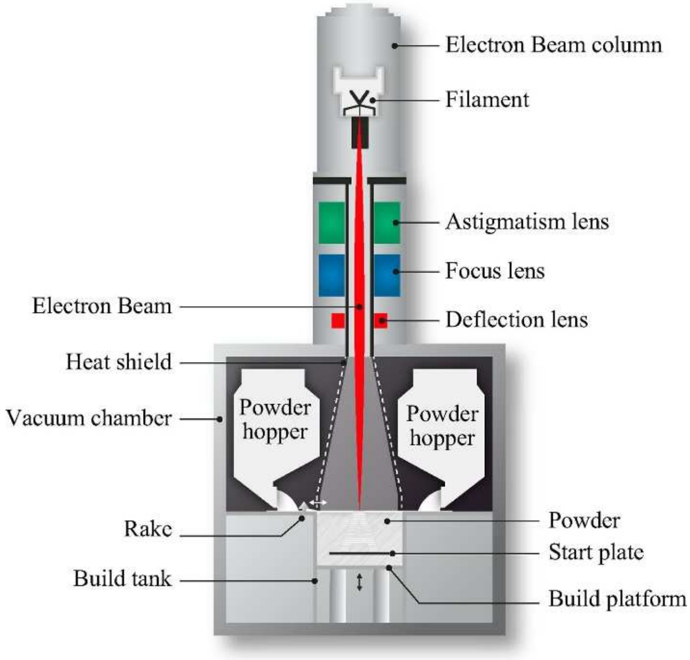


Figure 13 - Schematic of Electron Beam Melting process [35].

2.1.5.6 Sheet Lamination

Sheet Lamination includes the processes for which the feedstock is in the form of a sheet, which constitutes a layer in the build. The sheet is either cut to shape and then stacked to previous layers, or the sheet is bonded to the previous layer and then cut to form the layer geometry, as well as hatched in the non-part area to facilitate removal of the part at the end of the build [30].

The Laminated Object Manufacturing (LOM) is the main process of Sheet Lamination category. It is an effective rapid prototyping technology with a variety of application possibilities. Applying LOM in rapid tooling and pattern-making is especially advantageous because of the LOM object robustness, their wood-like properties and their comparably low material costs. Explicit application examples in sand casting, investment casting and ceramics processing show how a reduction of necessary process steps and cycle times can be achieved by the application of LOM models. Although not so predominant as other methods of additive manufacturing LOM technology can still be provided by several companies, which also offer other AM services [11, 36].

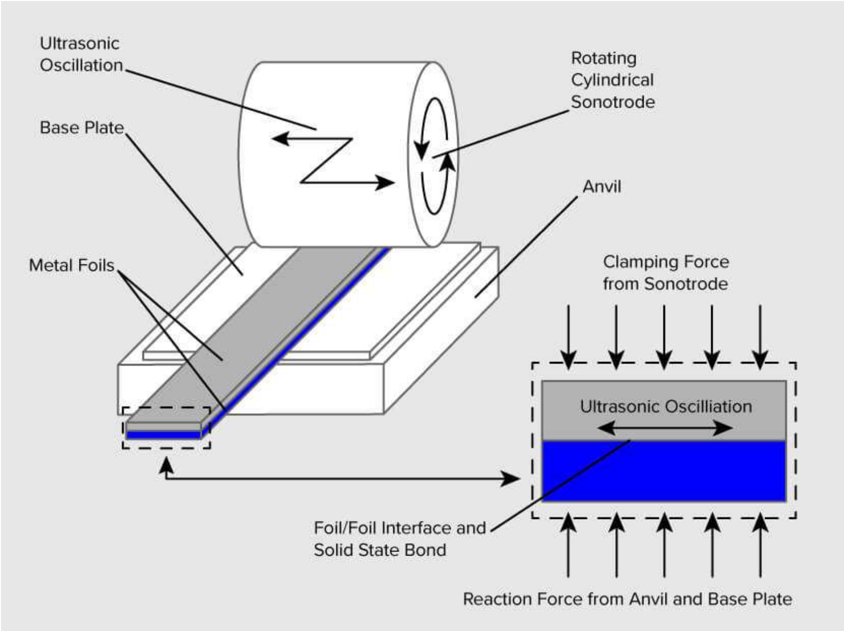


Figure 14 - Schematic of Sheet Lamination process [29].

2.1.5.7 *Directed Energy Deposition (DED)*

The Directed Energy Deposition category includes a collection of AM processes that use focused thermal energy to melt and bind materials fed in powder or wire form. The thermal energy source is usually a laser or electron beam. The molten metal solidifies when it is cooled down and generates the part [18, 30].

Directed Energy Deposition category is, along with Powder Bed Fusion, the most proven and feasible method when it comes to metallic parts. Unlike plastic or polymeric-based AM processes, DED and PBF require an electron beam or laser beam, or any thermal energy source, to accomplish layer-to-layer metallurgical bonding – to overcome the relatively high enthalpy of fusion and melting temperature of metals. Since a laser is usually used as energy delivery type for these processes, they can be referred as Laser-Based Additive Manufacturing (LBAM). DED combines the material/energy delivery for simultaneous deposition and part forming within a similar region, as shown in Figure 15 [37].

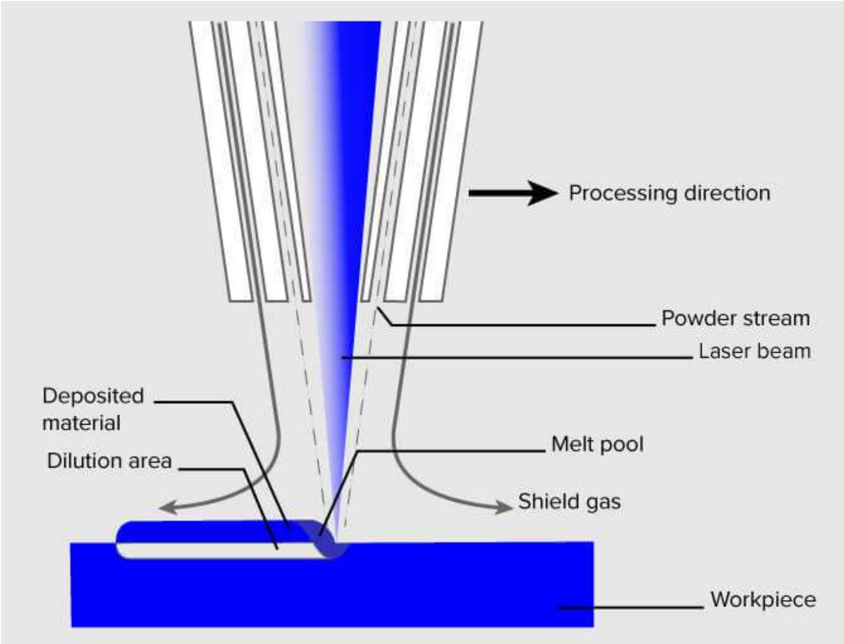


Figure 15 - Schematic of Directed Energy Deposition [29].

This process has the capability to produce large volume deposition rates (cm^3/min) and provides a relatively wide process window to fabricate larger items relative to other metal-based AM methods. Moreover, DED generates a relatively small heat affected zone (HAZ) on the part during processing. It provides excellent density and metallurgical bonding, a minimal effect on the component (e.g. distortion, micro-cracking) and a precise deposition. For these factors, DED is a widely used tool for repairing high-value components. Repair of damaged turbine blades made from nickel base super alloys as well as engine cylinder heads and blocks are two examples of such repairs [38]. This technology has also the potential to produce high quality parts to exact dimensions for aerospace, medical or military industries. Some common materials which have been investigated for DED include: titanium alloys, steels, nickel-based super alloys, cobalt-based alloys, aluminum and copper alloys [38].

Laser Engineered Net Shaping (LENS®): LENS is a AM method that produces metal components by combining a metal powder melting process with pre-designed 3D CAD model. This process is one of the pioneering technologies and, currently, the most successful commercial forms of DED. It is a trademark process created by researchers at Sandia National Laboratories in the mid-to-late 1990s which is a type of powder-based DED and include multiple nozzles for more effective powder delivery. The prime advantages of LENS are the ability to obtain near-net-shape thin-walled components with fine microstructure deriving from relatively high cooling rates and the possibility of making gradient structures, which allows joining of two totally different materials [37, 39].

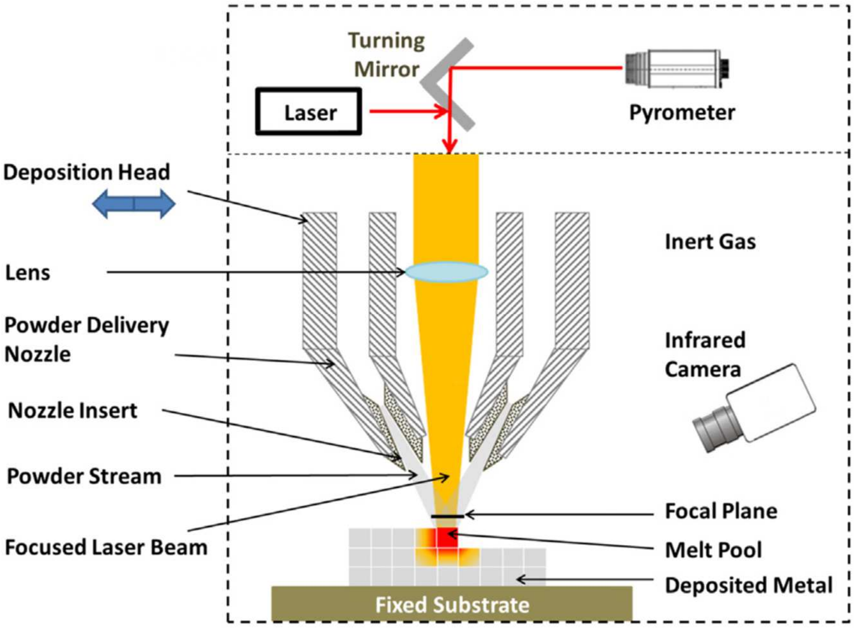


Figure 16 – Schematic of Laser Engineered Net Shaping system with thermal monitoring [37].

2.1.6 Applications

AM's direct digital workflow and freeform geometry can be combined to fabricate objects with any degree of customization and to offer a cost effective production of custom-fit and mass customized products (see Figure 17). This includes products that can be custom-fit to an existing person or object, products that can be personalized based on personal preferences and mass-customized products that can be produced with infinite variations.

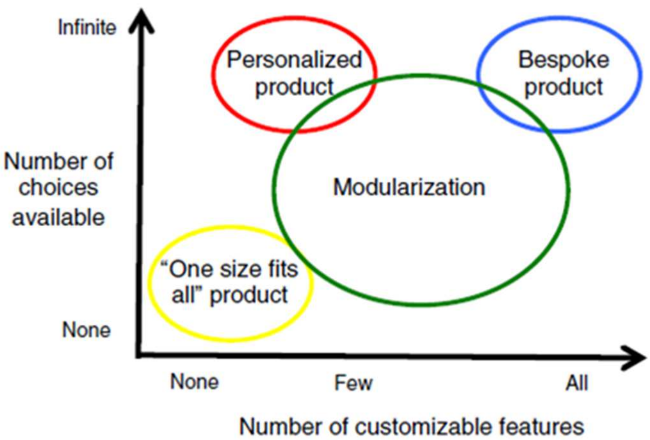


Figure 17 - Types of customization for AM technology [14].

In the medical and dental industries, AM is being used to produce a wide variety of personalized and bespoke products including hearing aids, dental crowns, implants and dentures biomedical implants for hard and soft tissues (see Figure 18); customized casts, splints, orthotics and prostheses [33].

Figure 18 - Cranial and hip implants made in titanium with a EOSINT M 280 machine (EOS 2015, EOS2 2015).

AM is also used to produce patient-specific models to facilitate surgical planning and surgical guides to improve accuracy and efficiency. For example, in orthopedic surgery, cutting guides are used to correctly position an implant for the individual patient’s anatomy. This improves the anatomical alignment of the implant and enhances the efficiency of the surgical procedure. AM surgical guides have the additional benefits of being lightweight (making them easier to handle during surgery) and disposable (safer) [14].

AM is also being used to produce custom-fit packaging and shipping materials. For example, according to the French researcher Barlier et al. [40], the Pack & Strat1 process from CIRTES, in France, uses a sheet lamination approach to produce custom-fit low cost ‘direct digital packaging’ for fragile and high-value objects. The process begins either with a CAD model or a 3D scan of the object to be packaged. The model is oriented and a bounding box is created around the model. The model is subtracted from the outer volume and the remaining volume is sliced. Next, the slices are arranged in sheets and the tool path is generated. Finally, the physical slices are cut from sheet stock, assembled around the object, bound and placed in the shipping container, as shown in Figure 19 [40]. This process is compatible with many types of material including cardboard, wood, cork, polystyrene, polypropylene and foam. It has been used to package industrial components, machine tools, artwork, crystal, glass, prototypes, models and more [14].

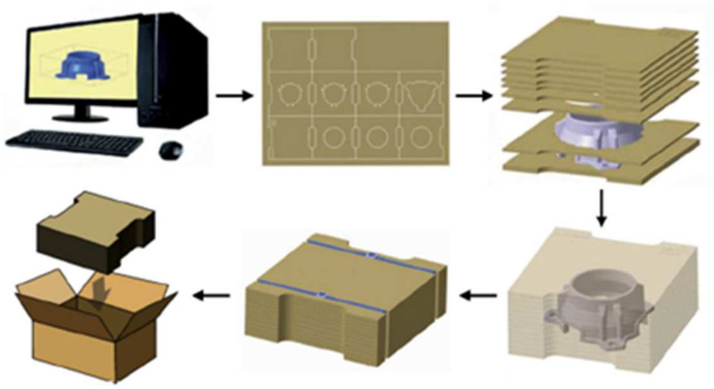


Figure 19 - Schematic of the custom-fit packaging process [40].

AM is being used to produce custom-fit consumer products, such as running shoes and ear buds; personalized products, such as eye glasses with customized messages; and bespoke objects, such as 3D busts created from photographs or 3D scans. Artists like Lionel Theodore Dean from FutureFactories.com are using AM to mass customize furniture, lighting fixtures and other home furniture, so that each part sold is unique. Finally, in the entertainment industry, AM is being used to produce mass customized models for stop motion animation [14].

2.1.7 Towards Industrialization

AM is on the edge of being broadly adopted in industrial practices. The world's top companies have already taken notice and they are making ambitious moves to capture their share of such potentially tremendous value. General Electric (GE), for example, has acquired two of the leading companies working in metal-based AM technology. BMW, GE, Google and Nikon are among the investors funding Silicon Valley startups, which are developing new polymer-based AM technologies. Also, Hewlett Packard has developed its own polymer-based AM process [41].

The Boston Consulting Group (BCG) has evaluated the size of the market for AM and they found out that it is actually booming [41]. By 2015, it had grown to approximately $5 billion USD. According to the consulting company, the trend is to keep growing at a compound annual rate of almost 30% through 2020, achieving a greater than threefold increase in size. They also assume that metal-based AM technologies will keep an increasing share of the AM market in the future, as can be noticeable in Figure 20 [41].

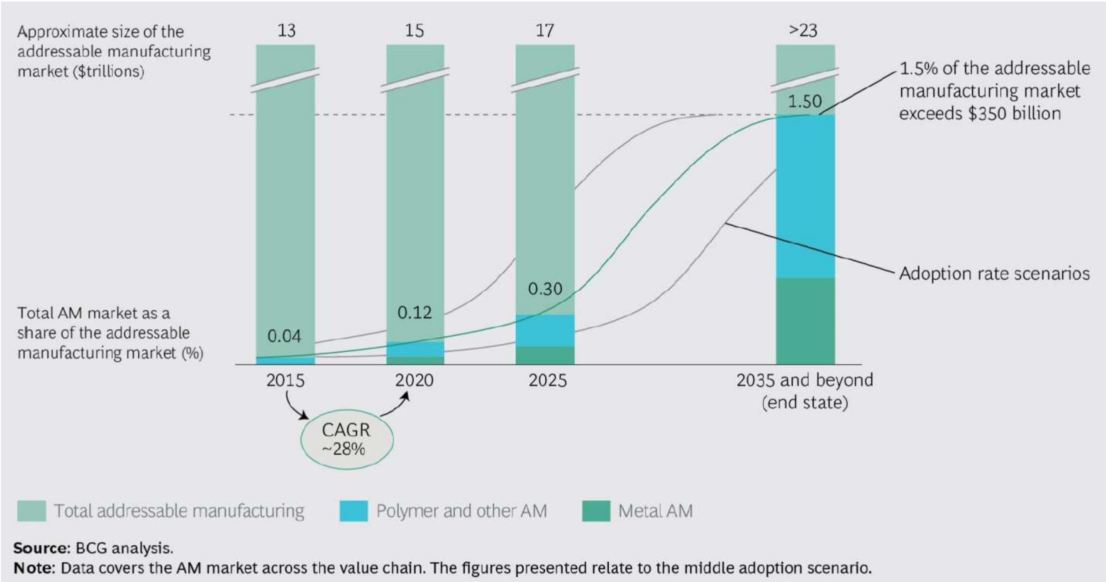


Figure 20 - Economic forecasting for AM market [41].

Following the BCG research, there are four dominant industries in AM - aerospace, dental, medical and automotive - and they will account for approximately 50% of the AM market in 2020. The attractiveness and adoption of AM will vary significantly among industries, although they all acknowledge the great potential of AM technologies to address unmet needs in industrial manufacturing. Thus, to evaluate an industry's state of adoption, there are three maturity stages that can be categorized. First the "R&D and Experimental": the AM processes is adopted for conducting tests and develop brand-new and innovative parts. Then, the "Prototyping and Making Spare Parts and Small Series": the manufacturers use AM to produce single parts or small series of parts and, in general, to use existing conventional designs for these parts rather than redesigning them to capture the benefits of AM. The third stage is the "Industrial Series Production": in this advanced stage, manufacturers use AM for large series and make the most of AM benefits. Indeed, AM technologies are critical to fulfil the vision of the factory of the future, in which manufacturers improve production by applying new design principles, implementing digital technologies and integrating processes across the value chain [41].

The adoption rate of AM at these three stages of maturity varies among industries. This state of adoption in each industry is described in Figure 21, in the order of their AM maturity.

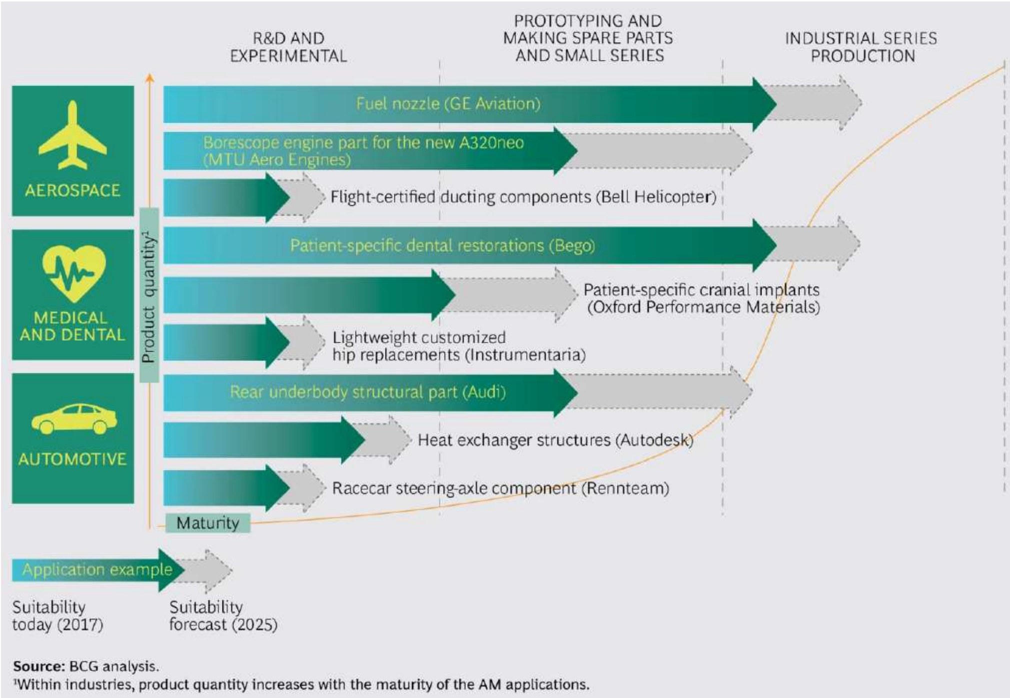


Figure 21 - Maturity of AM state of adoption in each different industry [41].

In the aerospace industry, the tendency is to optimize the shape of parts and create lightweight structures, thus contributing to reduce fuel costs. The main advantages that AM technologies bring to aerospace manufacturing are especially relevant for making components of propulsion systems and jet engines, cabin interiors, air conditioning, hydraulic and pneumatic systems; drones and satellites. In the case of Medical and Dental industry, manufacturers can cost-effectively produce medical implants and devices. AM's advantages are especially beneficial in hearing aids, orthopedics and prosthetics, and surgical guides and models. Looking further into the future, it can be expected the use of AM for producing drugs, tissue and organs. In the automotive field the manufacturers may use AM to produce tools and components. For instance, to build the Rolls Royce Phantom, BMW has used AM in series production to make more than 10,000 parts, such as plastic holders for center lock buttons as well as electronic parking brakes and sockets. The main benefit is the reduction of time, costs associated with product development and the simple customization of the parts [19, 41, 42].

Many large chemical and metal powder companies are already supplying the AM industry. Suppliers have a crucial role in the industrialization of AM and should step up efforts to promote it, although there are some challenges that suppliers have to address, in order to succeed. The range of materials should be broader and further developed, since industrialization requires an extensive materials portfolio and the available materials should match the requirements of specific target industries. Another goal for these stakeholders is to reducing the costs and for broad-based industrialization, AM materials must be cost-competitive. Additionally, enhancing the end-to-end supply chain is also required and the material providers must create a supply chain solution for their materials, that includes ensuring full traceability back to the source and offering to recycle used materials [19, 41].

Regarding the technologies, both polymer-based and metal-based AM processes are being widely adopted for high-volume industrial production. Established AM equipment providers are investing resources in the development of polymer-based technologies for industrial applications beyond prototyping. SLS and FDM are the most effective polymer-based processes for industrial applications. In the case of AM metal-based processes, the large manufacturers are also investing in industrializing them. Metal PBF has emerged as the leading technology of this classification for industrial part production. All of these particular technologies are expected to become even more dominant through 2025 [41, 42].

Compared to subtractive manufacturing, AM has always been particularly suitable for applications with low production volume. However, now is the time for players along the value chain to investigate the opportunities that AM offers and make industrialized AM a reality [41].

2.1.8 Advantages and Disadvantages

AM offers noticeable advantages. First, as a result of the additive approach, AM processes are capable of building complex geometries which could be very difficult or even impossible to be manufactured by other conventional processes. Thus, AM offers the utmost geometrical freedom in engineering design. This unique feature allows saving of material (product cost) and weight (operational costs) by design topological optimization [12, 43].

The absence of waste material, like chips resulting from machining, is a considerable AM advantage in terms of saving energy, material, tooling (e.g. molds, dies, fixtures or jigs) and manpower, being consequently environmentally sustainable. Due to its capability of making physical objects in a relatively short time, directly from virtual CAD data, AM also presents easy application on reverse engineering to generate new parts, almost identical, by means of 3D scanning of existing parts, instead of a completely new design. Consequently, new opportunities exist for design in industries as diverse as automotive, aerospace and bio-engineering. Additive techniques enable rapid response to markets as the possibility to produce on-demand spare parts, cutting down or eliminating the production development step and the need for stockpiles [5, 11, 18].

Furthermore, it is possible with AM to create functional parts without the need for assembly, reducing the overheads associated with documentation and production planning. This process offers reduced waste, minimal use of harmful chemicals, such as etching and cleaning solutions and the possibility to use recycled materials. Additionally, AM allows to manufacture parts with an improved design and made in a single integrated part, as represented in Figure 22, thus minimizing the number of components. Still about the creation of new parts, the customization and the performance optimization are two distinguished advantages of the mentioned technology. Therefore, with recent developments in the synthesis of end-use products from multiple materials (including metals, plastics, ceramics, etc.) and its inherent environmentally-friendly nature, AM has emerged as a transformative technology in innovation-based manufacturing [12, 19].

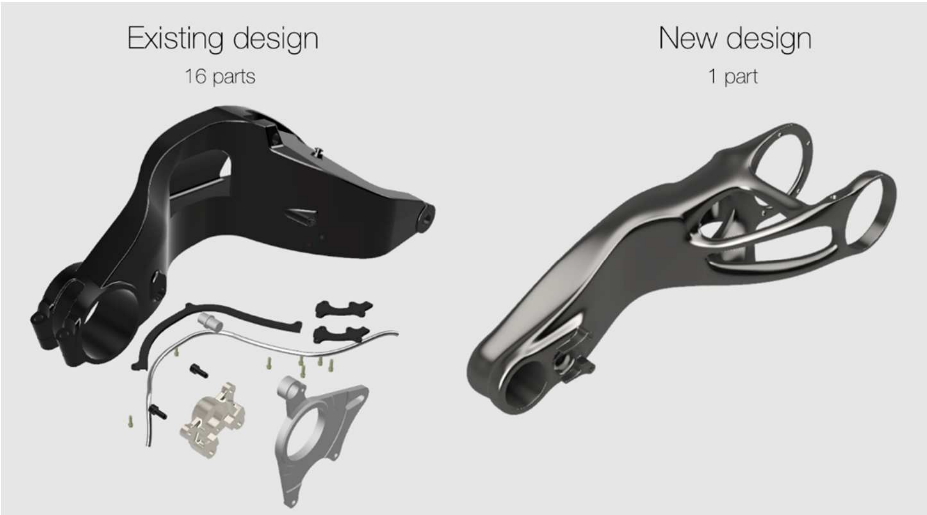


Figure 22 - Part redesign and minimization of components.

While AM has been largely integrated into today's society and breaking new grounds, there are some limitations and disadvantages to the process. Beginning with the operating costs, the machine price and the building material costs are normally high in this type of technology. Some AM materials are expensive because they are costly to produce and their volumes are relatively low compared to materials for conventional manufacturing. The surface finishing is also a significant concern. This is the primary downside of the process and regardless the type of the process, the surface finish and dimensional accuracy may give less quality than other manufacturing methods. For this reason, the produced parts might require post processing. Another major issue is the almost unavoidable usage of support structures upon the building stage. Also, the anisotropy of the outcoming part, as well as, its layering and multiple interfaces turn it out with low mechanical properties. One more limitation is the component size, which is limited by the building volume of available AM machines. AM cannot create products such as vehicle parts or aircraft wings. Also, considering those products created from AM using liquid polymers or powders consisting of resin or plaster, large products are not currently a viable option. In conclusion, the designers may have to rethink their approach focusing on the best solutions to exploit all the benefits of AM techniques and taking into consideration its limitations [11, 19, 44].

2.1.9 Costs

According to Wohlers Report, the global revenue of AM was estimated to be about $967 million USD in 2013. Out of this, the United States of America contributed with an estimated $367 million USD or 38% of global production. In the detailed analysis, the current manufacturing cost and evaluation of expected improvements reveals a cost reduction potential of around 60% in the next 5 years and another 30% within the next 10 years. Considering the current scenario and future development, the AM has sufficient room to grow in several industries [10, 19, 45]

AM is often an expensive technology although it is regularly used for the manufacturing of an increasing number of parts and products. It is a crucial procedure to comprehend and evaluate the realistic cost justification for its use. Thus, there are two major categories for examining AM costs [10, 19].

One approach is to compare AM processes with conventional manufacturing processes. However, by doing this comparison analysis, the range of products for which it is suited will possibly be small and a business case for investing in AM that relies on this approach will likely fail. Instead, the entire product life cycle and total manufacturing cost should be considered. For instance, an airplane part that costs $1000 USD using AM compared to $500 USD by casting does not sound promising. However, if its weight is reduced by 25%, resulting in a $5000 USD reduction in 10-year operating costs, a business case can be made. Similar arguments are possible for improvements in product function, greater customer satisfaction, reduced product maintenance and a reduction in total manufacturing costs. Therefore, the purpose of this type of analysis is to figure out under what circumstances AM is cost effective.

A second approach involves identifying resource use at each and every stage in the AM process. The purpose of this type of analysis is to identify when and where resources are being consumed and whether there can be a reduction in resource usage. Along these lines, this second category is being approached in this chapter.

In this cost analysis all the steps needed to manufacture the part should be considered. Thus, the cost for producing the raw material may be the initial variable to be considered. Examples of operations which make part of this step are the gas atomization in the case of the metal powders and the injection for producing the wire in the FDM process. Still concerning the material, the logistics operations like storage and stocking shall be also considered. Then, the digital definition of the part must be complete before the build can begin. This is an obvious but often overlooked cost when companies evaluate AM technologies for production. CAD software licenses, build preparation software and skilled CAD operators are required. Due to the technical requirements of part building, this step can also be more complicated than expected. The first time a part is built, it might have dimensions that cannot be brought into tolerance with post-processing machining, or it may experience distortion from thermal stresses.

Thereupon, the pre-processing steps require corrections. The technician may need to change iteratively the CAD model, reorient the part in the build chamber or optimize the supports that anchor and secure the part to the build plate. An insufficient number of supports, or their size and location, can have an impact on the thermal distortion of the part. Too many or improperly located anchors can significantly increase post-processing time and cost. This iterative process is repeated until satisfactory results are achieved. At the point of the process itself and when the part is performed by the AM machine, the predominant costs associated are the machine set-up (pre-processing), the labor for machine operation, gas rental and use, gray water disposal and power supply (building), thermal treatments, if required, shot peening, support removal and rework (post-processing). Furthermore, the costs related with the finishing after the part is built, such as machining or painting, are still relevant and ultimately the quality control costs shall be considered, which involves administrative costs. These mentioned process steps are illustrated in the Figure 23 [11, 19, 44].

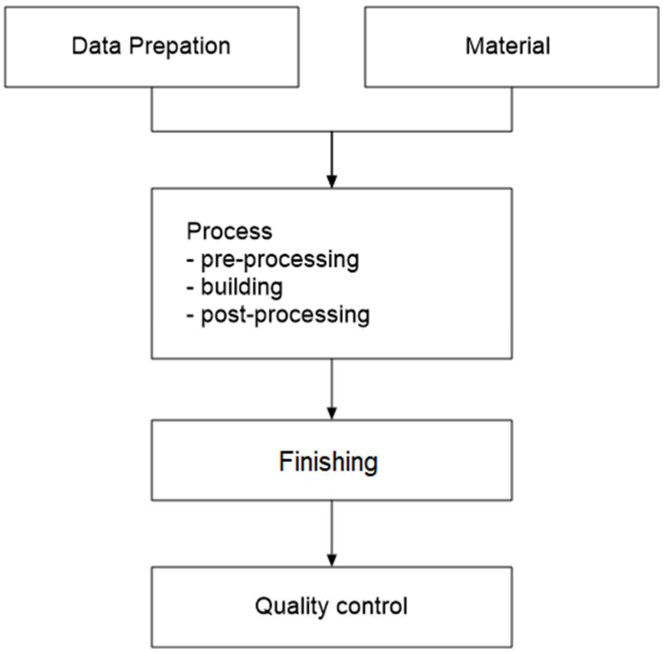


Figure 23 - Flow chart of the AM process steps concerning their costs.

Several cost models have been proposed in the past. In this section, two of main existing cost models are analyzed in order to give a brief overview of the approaches used by each author.

Hopkinson and Dickens [46] carried out a generic analysis of the rapid tooling and rapid manufacturing costs. The authors developed a method allowing for the manufacturing of finished products on a large scale. Hopkinson and Dickens reported a cost analysis that compares the traditional manufacturing method of injection molding with layer manufacturing processes (Stereo Lithography, Fused Deposition Modelling and Laser Sintering) in terms of the unit cost for parts made in various quantities (see Figure 24). The results showed that, for some geometries, up to relatively high production volumes (in an order of a thousand parts), it is more profitable to use the layer manufacturing methods. The costs of the parts were broken down into machine costs, labor costs and material costs, as expressed in equation 1. The energy was neglected, due to its low impact on costs.

$$Total\ cost\ per\ part = Machine\ cost\ per\ part + Labor\ cost\ per\ part + Material\ cost\ per\ part \quad (1)$$

The proposed model provides a first approximation of the production costs. These costs were calculated assuming that a machine produces one part constantly for one year. The material used for production is polyamide. The work was performed when the technology was not yet matured; different aspects of Hopkinson and Dickens' research were further developed by other researchers [1, 47].

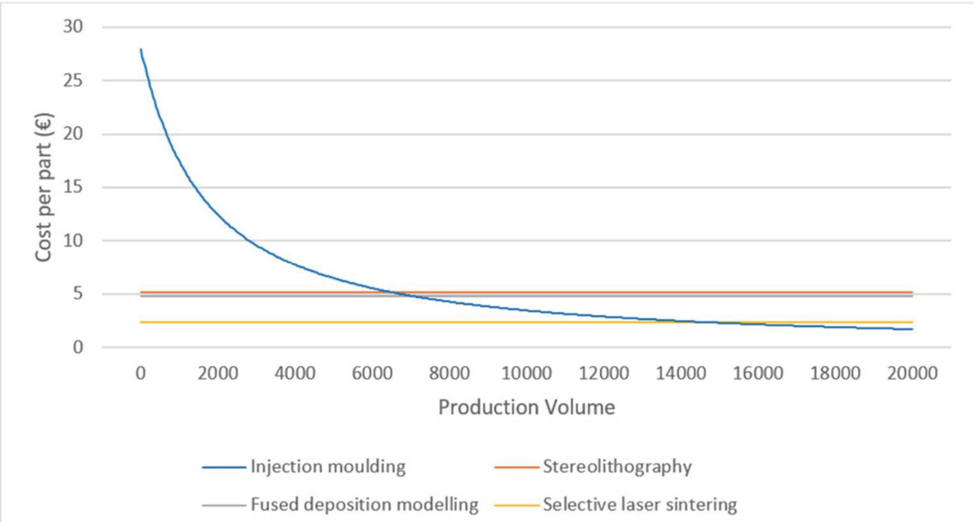


Figure 24 - Cost comparison with different processes based on work by Hopkinson and Dickens [1].

Alexander et al. [48] performed a cost model with a deep analysis of the steps involved, including all the pre and post-processing steps linked to AM processes. The cost of the single part (Pi) is obtained by adding the costs of the seven processing steps defined by Equation (2). This equation is based on the generic cost model of Alexander et al. [42, 48]:

$$C_{Total}(Pi) = C_{prep}(Pi) + C_{build\ job}(Pi) + C_{setup}(Pi) + C_{build}(Pi) + C_{removal}(Pi) + C_{substrate}(Pi) + C_{postp}(Pi) \quad (2)$$

where

Pi: part with *ith* geometry,

C_{tot} (Pi): total manufacturing costs,

C_{prep} (Pi): cost for preparing geometry data (orientation, support structures, etc.),

$C_{build\ job}$ (Pi): cost for build job assembly,

C_{setup} (Pi): machine set up costs,

C_{build} (Pi): cost for building up the part,

$C_{removal}$ (Pi): cost for removing the part from the SLM machine,

$C_{substrate}$ (Pi): cost to separate parts from substrate plate,

C_{postp} (Pi): cost for post-processing.

2.2 Directed Energy Deposition (DED)

Directed Energy Deposition (DED) is an established and well-known Additive Manufacturing category performed with metallic materials which can be either operated with powder or wire feed. Currently, this technology is at the peak of its expectations and it is emerging within the AM processes. Additionally, it is a promising technology with growing research interest, being these reasons for a deeper analysis in this section and the base technology for current work.

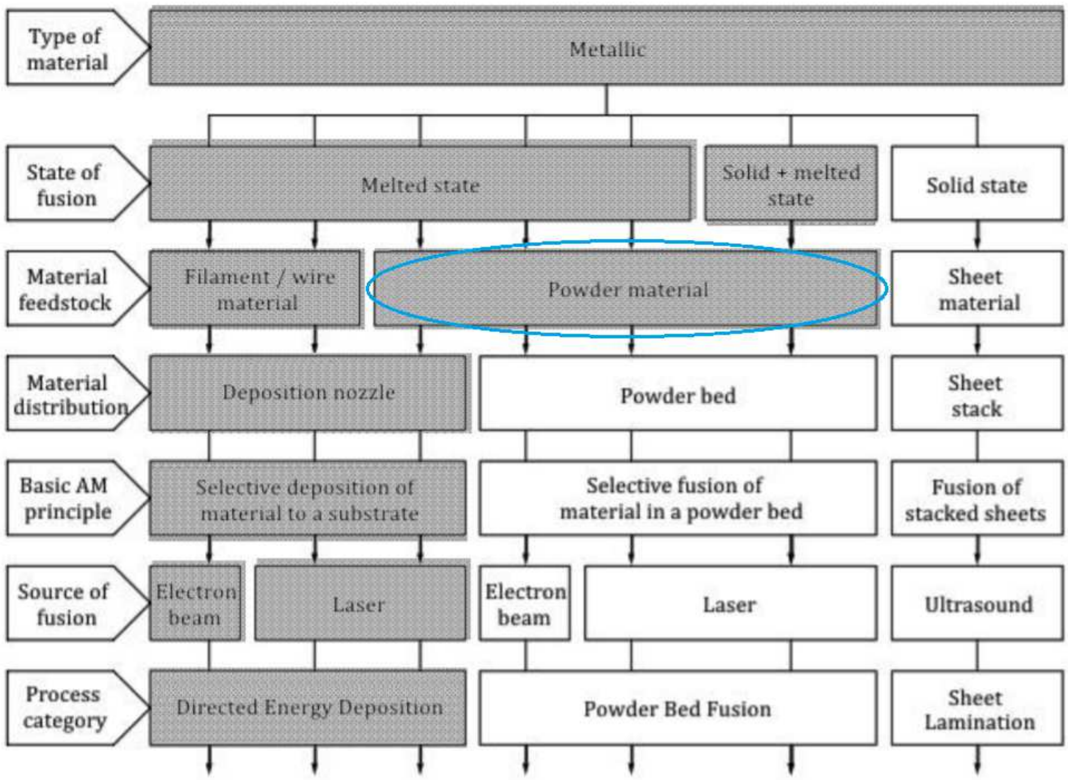
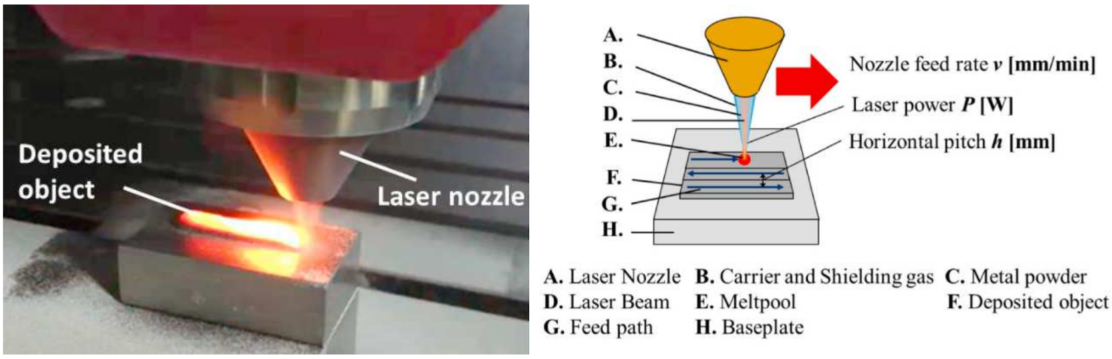


Figure 25 - Morphological box for metal based AM processes [49].

2.2.1 Description

DED process creates products by melting the baseplate with a laser beam and then depositing powdered material to the melt pool, as shown in Figure 26 (a). By heating metal powder with a high-power laser and controlling melting and solidification continuously, DED produces the expected shape of metal parts. All the variants of this technology employ an integrated Powder Delivery System (PDS), which consists primarily of a single or multiple coaxial nozzles with local shielding of melt pool and pumped powder feeding lines. The powder may be injected through an inert carrier gas or by gravity feed. Also, a separate supply of shielding gas is used to protect the molten weld pool from oxidation, as displayed in Figure 26 (b) [37, 50, 51].



(a) (b)

Figure 26 - DED process; (a) real schematic with main elements [50]; (b) schematic illustration of DED [50].

This technology is the key method for producing a near-net-shape product. Near-net-shape is an industrial manufacturing technique which enables cost and lead time reduction through minimization of processing steps (in particular, cutting and finishing operations) and raw material saving [52].

Concerning the DED benefits, this technology is suitable for coating, repairing, building and rebuilding parts having very complex geometries. Also, the high degree control of grain structure, the capability to feed different powders at the same time into the melt pool and the part dimensions not being limited are attributes of this technology. Minimal distortion of the workpiece, reduced heat-affected zones and better surface quality are benefited in comparison with conventional coating and repairing techniques, such as arc welding or plasma spraying. Even further advantages are obtained in terms of processing speed due to new generation of high brightness lasers, with increased beam quality. Enhanced productivity is also benefited and grounds are given for automation and reduction of the overall processing time. These features are required in adaptive and flexible manufacturing environments and factories of the future [53-55].

Some current drawbacks of utilizing DED is the relatively low powder efficiency and quite rough, post-DED surface finishes, as well as the fact that is limited to metals and metal-based hybrids [38, 56].

Regarding the inert gas employed in DED, this element is used to facilitate powder flow and to minimize high oxidization rates inherent for elevated temperature metal processing. Since the melting temperatures of many metals are considerably high, parts are heavily prone to oxidization during DED. Therefore, inert gases, such as Argon (Ar), diatomic Nitrogen (N2) and Helium (He), are required to help in displacing oxygen within the DED machine chamber and PDS [37, 57].

2.2.2 Mechanism

DED is a layer by layer AM technique to build metallic and functional components. In this process, powder is usually fed into a laser-heated spot to form a molten pool, which solidifies quickly after the laser beam moves away. The whole physics is very complex, involving processes such as laser-powder interaction, laser substrate interaction, track interface evolution and melt-solid interaction. Each process contains a number of processing variables, some of which are coupled with each other. Due to the involved complexity of laser deposition processes, many models have been developed in a simplified way, e.g., neglecting the fluid motion in the molten pool or using predefined clad geometry. Conduction heat transfer models were adopted to predict the thermal behavior during laser deposition without considering fluid motion in the molten pool [58].

The powder-based DED consists, in this way, of many interconnected, coupled physical events – all occurring at a very short time scale. For a given instant in time, there are several possible paths for momentum and energy transfer. As shown in Figure 27, this energy and/or momentum transfer can be categorized as to occur either subsequently or in-parallel. Some of these physical events, in order of approximate occurrence, include: laser delivery, particle/powder delivery (energy and dynamics), laser/powder/gas interactions, melt pool initiation (melting), melt pool energy/stability/morphology, heat loss to environment via thermal radiation and convection, solidification, intra-part conduction, thermal cycling and part-to-substrate conduction. Some of the detailed physical 'sub-events' for each category are provided in Figure 27. These sub-events within the DED processes have been investigated for the past few decades, either directly in the field of DED or in similar manufacturing processes, such as laser welding/cladding. Affiliated with these physical events are the DED process parameters and for a given combination of these parameters, for a specific material and machine, a fully dense, structurally sound part can be generated. These parameters include, naming only a few: material density, material thermal conductivity, laser beam diameter, laser power, traverse speed, powder feed rate, powder size, gravity and more. Non-dimensional groups include: process efficiencies – such as energy loss, melting, superheating and powder delivery – and classical non-dimensional variables, such as the: Bond, Froude, Galileo, Prandtl and Reynolds numbers. Geometric non-dimensional parameters were also found and include: non-dimensional length of melt pool, melt pool shape factor and a powder dissolution factor [37].

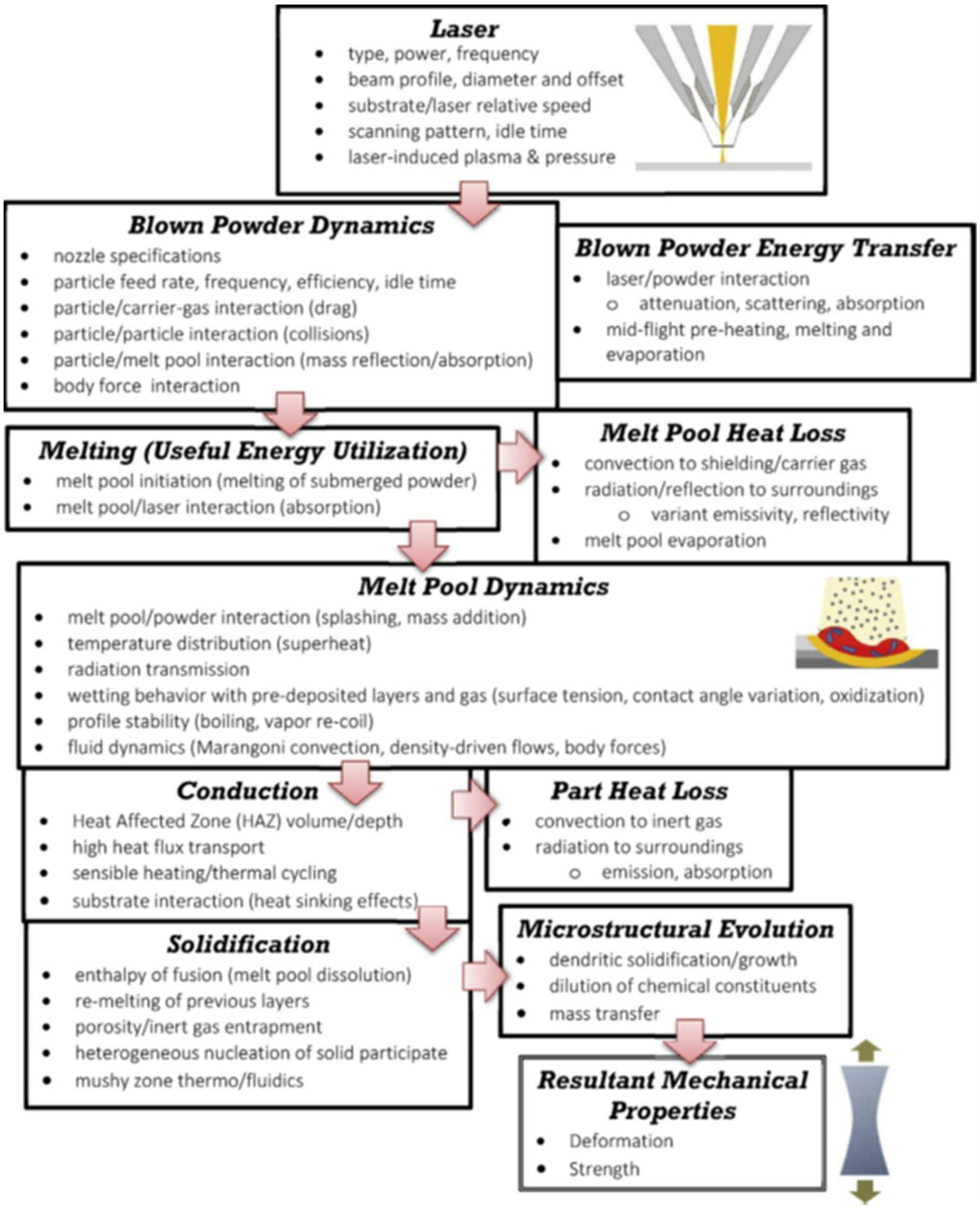


Figure 27 - Physical events occurring during powder-based DED for a given instant in time [37].

2.2.3 Producers

Manufacturers of DED systems work with laser as an energy source and powder is usually fed coaxial to a laser beam with inert gas. Depending on the feed nozzle, it is possible to manage speed and accuracy (coaxial nozzle gives the highest accuracy, off axis is the fastest). Most DED systems use a 4 or 5-axis motion system or a robotic arm to position the deposition head, so the build process is not limited to successive horizontal layers on parallel planes. This capability makes the process suitable to adding material to an existing part, such as repairing a worn part or tool. In other systems, the part is moved under a stationary deposition head [59, 60].

Table 2 presents a list of equipment manufacturers and their equipment for DED with powder feed techniques. The high-power laser often adopted is the fiber laser, although the Nd:YAG and CO^2 laser are also used. Regarding the dimensions, this equipment uses an ample working volume, making it ideal for repair, rework and modification of large industrial components. As an example, the LENS 850-R system (shown in Figure 28) from Optomec holds a building volume greater than 1.2 m^3, having the capability to provide a resulting part with mechanical properties that can be equivalent to or superior than the original component [61].

Table 2 - AM equipment manufacturers and corresponding specifications [62].

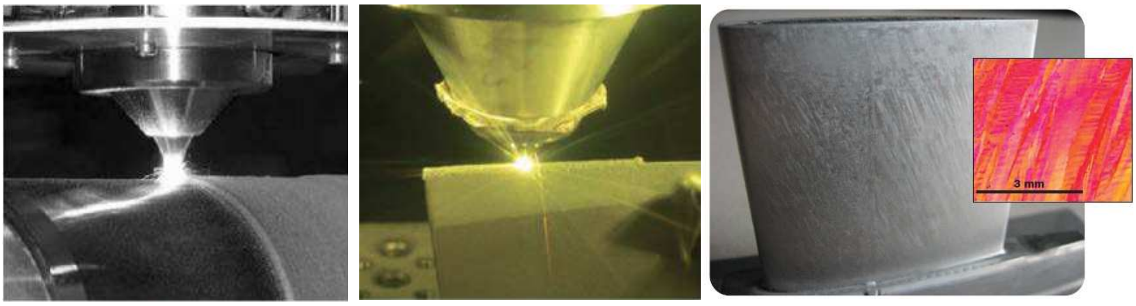
System	Process	Build Volume (mm)	Energy Source
Optomec (LENS 850-R) (a)	LENS	900 x 1500 x 900	1 or 2 kW IPG fiber laser
POM DM3D (66R) (a)	DMD	2330 x 1670 x 1670	1-5 kW fiber diode or disk laser
Accufusion laser consolidation (b)	LC	1000 x 1000 x 1000	Nd:YAG laser
Irepa laser (LF 6000) (c)	LD		Laser cladding
Trumpf (d)	LD	600 x 1000 long	
Huffman (HC-205) (a)	LD		CO_2 laser cladding

Country of Manufacturer: (a) USA; (b) Canada; (c) France; (d) Germany

Figure 28 - LENS 850-R DED System [61].

2.2.4 Applications

Since the deposited material in DED is fully dense, its mechanical and physical properties are as good or better than those of comparable cast or wrought materials. DED has been widely used in many industrial applications such as surface coating, innovative alloying, low-volume manufacturing, high-value component repairing, rebuilding long lead-time components (particularly in the defense industry), hard facing for extended life in tools, dies, cutters, etc., as well as applications of conformal cooling in injection molding tools. Besides near-net-shape part manufacturing capability, controlled heat input during the DED process allows building parts with desired microstructures. An example is an Inconel (nickel-based super alloy) turbine blade built with the controlled crystal structure, as presented in Figure 29 (c). This model blade demonstrates the potential of DED technology to build up or repair turbine blades with directionally solidified structures [54, 58, 63].



(a) (b) (c)

Figure 29 - DED applications; (a) surface coating [64]; (b) high-value component repairing [65]; (c) high-performance metal components fabrication [54].

The DED processes have several applications in medical industry and aerospace sector. Shortened lead-times and new possibilities in the position of closed cooling channels make the technology quite attractive for the market. For instance, cooling channels close to the surface, as shown in Figure 30 (c), that are not producible by conventional technologies, can shorten heat and cooling cycles. Respecting to the medical field, these technologies offer the possibility to manufacture osseo-integrative structures such as lattices and thus improves the functionality of implants [27, 59, 62].

(a) (b) (c)

Figure 30 – Parts produced by DED; (a) Example of metal parts fabricated using LENS; (b) fine grid structure for use in the medical field; (c) airfoil with embedded cooling channels (material: Ti-6Al-4V) produced by LMD [27].

Regarding the materials which are processed by this technology, those are usually titanium alloys, stainless steels, tool steels, nickel-based super alloys, cobalt alloys and aluminum alloys. Ti-6Al-4V has been by far the most extensively investigated alloy in DED processes. It is the most frequently used titanium alloy in the aerospace, automotive and biomedical industries because of its excellent mechanical strength, fracture toughness, low specific gravity and corrosion resistance [27, 59, 62, 66].

AN INTEGRATED COST-MODEL FOR DIRECTED ENERGY DEPOSITION (DED)

3 AN INTEGRATED COST-MODEL FOR DIRECTED ENERGY DEPOSITION (DED)

In this section, a study and analysis is performed about the costs related with Directed Energy Deposition technology. The purpose of this study is to determine the cost effectiveness of this technology and to better understand how adequate and profitable it is, when compared with similar manufacturing techniques.

3.1 Cost Estimation

Cost estimation is related to the prediction of the costs involved with a sequence of activities before they have actually been executed. The cost estimation of a product can be performed using quantitative models or historical data. This prediction helps companies to identify business potential, determine the product price, perform break-even analysis and prepare budgets. Cost estimation is convenient for serving the customer with accurate quotations.

The cost of the product relies fundamentally on the resources used to manufacture the product. These resources are cost components of the products such as material, machine, labor or tooling. To evaluate the product cost, the costs associated with these components should be estimated.

This analysis, concerning the DED technology, can be carried out using two methodologies. A first possibility is to compare the set of DED processing activities with conventional manufacturing processes. A second path involves identifying and analyzing the resources used at each and every stage in the DED process chain. Accordingly, it can be recognized when and where the resources are being applied and whether there can be a reduction of resources being used.

3.2 Cost Comparison

The several costs associated with a manufacturing process can be broken down into assorted categories. For that reason, various studies have been made in order to compare cost structures of an AM technique with those of a conventional manufacturing method. According to Hopkinson et al. [46], Allen [67], Ruffo et al. [68], Atzeni et al. [44] and Thomas [69], the cost categories considered include generally material cost, labor cost, machine cost and administrative cost. However, the cost categories which appear to be more accurate to perform a cost structure analysis, when comparing AM with conventional manufacturing processing, were the ones adopted by Li et al. [70]. Li mentions four main cost categories were the following: transportation cost, manufacturing cost, administrative cost and inventory cost. The purpose of the study made by Li was to investigate the impact of AM on spare parts supply chain. Three supply chain scenarios were investigated in his research, namely conventional supply chain, centralized AM-based supply chain and distributed AM-based supply chain. In this study, Li specifically compares those supply chain scenarios in terms of total variable costs. The cost structures differences of the four categories adopted by Li between the conventional spare parts supply chain and the one adopting an AM technology are presented in Table 3.

Table 3 - Cost structure comparison between conventional supply chain and the one adopting AM (adapted from Li et al. [70]).

Cost Category	Conventional supply chain	Supply chain adopting AM
T: Transportation cost	Material (from supplier to manufacturer); Product1 (from manufacturer to distributor); Product2 (from distributor to service location).	Material (from supplier to distributor); Product (from distributor to service location).
M: Manufacturing cost	The labor, material and machine cost.	The labor, material and machine cost.
I: Inventory cost	The cost to the distributor and manufacturer.	The cost to the distributor; For a decentralized supply chain, there is no inventory at the distributor
A: Administrative cost	The cost to the supplier, manufacturer and distributor.	The administrative cost to the supplier and distributor.

By analyzing the Table 3, there are a few differences noticed between the supply chain from a conventional process and from an AM process. One of those differences can be identified in the transportation cost category. Thus, traditional manufacturing has diverse intermediate products that are transported and assembled, whereas AM can complete an assembly in a single build. It is in an assembled product where AM might have considerable cost savings. Considering the manufacturing cost category, there is no discrepancy between the two supply chains. However, in inventory and administrative cost categories some differences can be seen regarding the costs to the manufacturer, due to the probable intermediate parts costs mentioned above [69].

Based on the cost categorization given in Table 3, a product life cycle costing diagram of a Directed Energy Deposition process has been created, as illustrated in Figure 31. The process starts with the powder production, this step can be placed in both administrative and inventory cost categories. Since the powder is used as raw material for the AM machine, this involves a transportation cost. Regarding the AM machine processing step, there are manufacturing costs, administrative costs and inventory costs related either to the powder and with the parts produced. The post-processing step involves also transportation costs, since the parts come from the machine location. Still concerning the post-processing, there are associated manufacturing, administrative and inventory costs. Additionally, related with the final user, there are costs such as inventory and transportation costs for the final product, as well as the costs linked with process planning, scheduling, etc. for the design of the part to be produced.

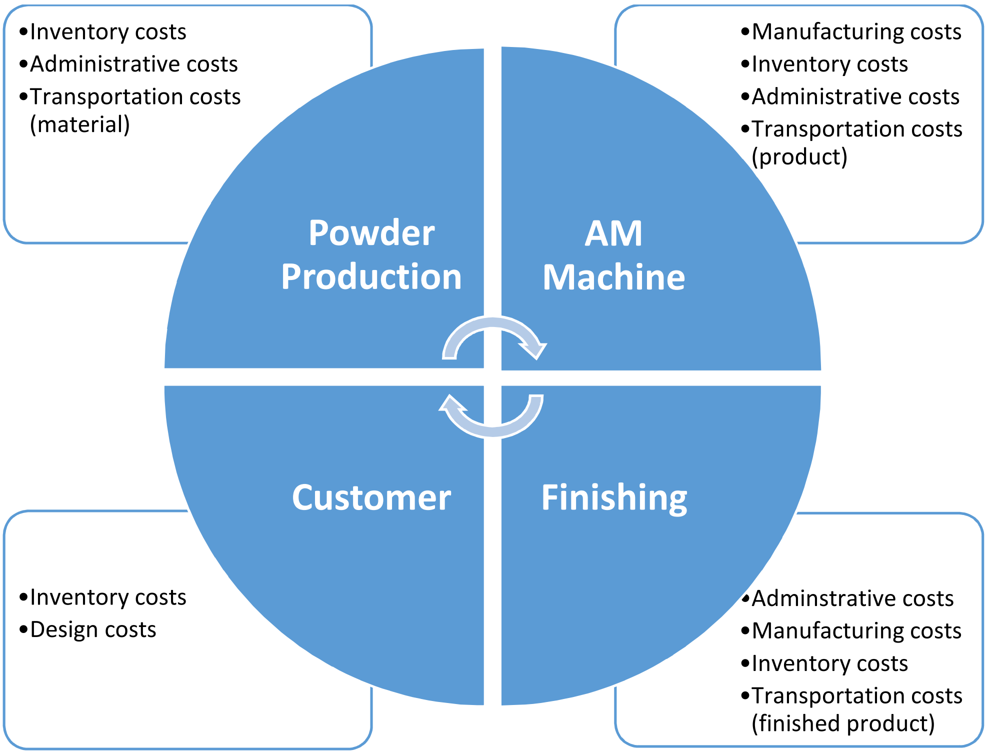


Figure 31 - Product life cycle costing diagram of a DED process.

3.3 Costs by Processing Steps

The cost analysis by processing steps is carried out in this section and involves the study of every step necessary to manufacture a DED part. Within every DED process, there are four essential stages to be considered: build preparation, manufacturing, finishing and quality control. Each of them considers all the diverse operations of the manufacturing process, as shown in Figure 32.

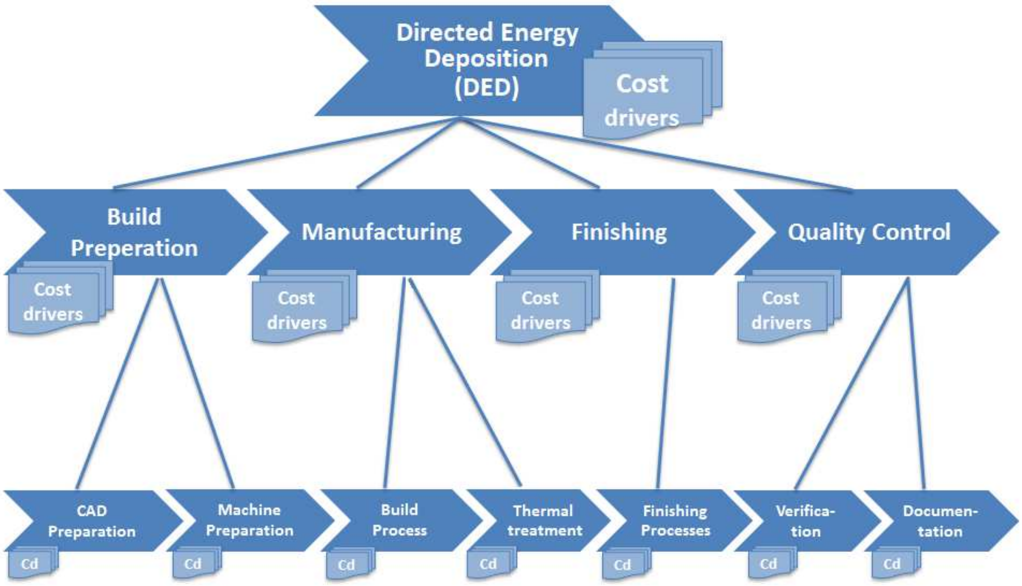


Figure 32 - Cost drivers of DED process (adapted from Lindemann et al. [71]).

3.3.1 CAD Preparation

At the beginning of the DED process chain one should prepare the data for the 3D design and production program. The 3D model is created by the CAD software which additionally needs corrections and error checking. This operation involves the time spent to carry out the CAD preparation (t_{cp}), the labor cost (C_{labor}) and the overheads charge (C_o), such as software licenses and administrative costs. Therefore, the CAD preparation costs (C_{cp}) can be simply given by:

$$C_{cp} = t_{cp} \times (C_{labor} + C_o) \tag{3}$$

3.3.2 Machine Preparation

The machine preparation is part of the building preparation stage. This pre-processing step involves a few imperative procedures which are crucial in order to guarantee the proper functioning of the building process. Firstly, it is required to perform the operation of holding and locking the build platform. The cost related with this operation ($C_{holding}$) is involving essentially the time required to perform the operation ($t_{holding}$), the labor cost (C_{labor}) and the machine cost (C_{mach}) which corresponds to the total machine hourly rate and the respective calculation is further explained in section 3.3.3.2. This cost is given by the following equation:

$$C_{holding} = t_{holding} \times (C_{labor} + C_{mach}) \tag{4}$$

The next operation is the powder preparation which generally includes sieving the metal powder and filling the powder feeder with it. The subsequent costs are determined by the time needed for the powder preparation (t_{pp}), the related labor cost (C_{labor}) and the machine cost (C_{mach}). Thus, the powder preparation cost (C_{pp}) is given by:

$$C_{pp} = t_{pp} \times (C_{labor} + C_{mach}) \tag{5}$$

The laser calibration, or laser alignment, is another machine preparation procedure which involves the time to calibrate the laser (t_{lc}), the labor cost (C_{labor}) and the machine cost (C_{mach}). The laser calibration cost (C_{lc}) can be expressed as:

$$C_{lc} = t_{lc} \times (C_{labor} + C_{mach}) \tag{6}$$

Then, the inert gas preparation, which basically consists in supplying the gas in the chamber, is depending on the time (t_{gp}), on the labor cost and the machine cost (C_{mach}), as shown in the following equation:

$$C_{gp} = t_{gp} \times (C_{labor} + C_{mach}) \tag{7}$$

To sum up, the machine preparation costs (C_{mp}) are function of the time to set-up the machine (t_{set-up}), the labor cost (C_{labor}), the machine cost (C_{mach}) and also the platform cost ($C_{platform}$). This is given by:

$$C_{mp} = t_{set-up} \times (C_{labor} + C_{mach}) + \frac{C_{platform}}{N} \tag{8}$$

where the t_{set-up} is the sum of all the time required to perform all the machine preparation procedures, which is the time for holding the platform, the powder preparation time, the laser calibration time and the inert gas preparation time and also the N is the number of parts produced by using the same platform.

3.3.3 Build Process

The build process step belongs to the manufacturing stage and it is the most significant and solid step when considering involved costs. The build costs (C_{build}) are given by the following equation:

$$C_{build} = C_{fixed} + C_{variable} \qquad (9)$$

The first costs to be acknowledged are the fixed costs. These costs have to be met regardless of the production volume. They are the sum of the costs related to small maintenance (C_{sm}) and the gas fixed costs (C_{gas}), which can be expressed as:

$$C_{fixed} = C_{sm} + C_{gas} \qquad (10)$$

Secondly, the variable costs are the costs determined by the machine hourly rate and the build time (t_b), as represented by equation 11.

$$C_{variable} = M_{hourly\ rate} \times t_b \qquad (11)$$

At this point, the build costs can be naturally broken down into four parts: the small maintenance costs, the gas costs, the machine hourly rate and the build time. The build process costs and their respective components may be seen in detail in figure 33.

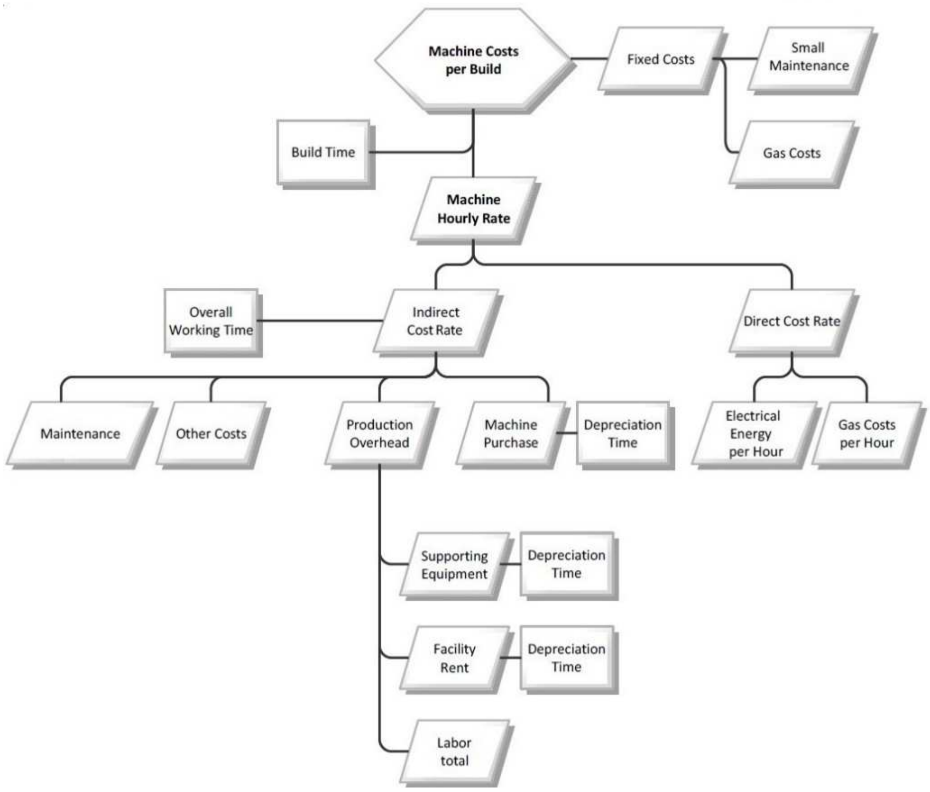


Figure 33 – Costs of build process (adapted from Lindemann et al. [71]).

3.3.3.1 Build Time

The build time (t_b) is one of the most influential aspects of the build process costs. This variable can be roughly estimated by considering the machine deposition rate and the volume of the raw material used in the manufacturing process.

Example:

To calculate build time, a practical example can be applied with the DED system LENS® 850-R from Optomec and with the titanium alloy Ti-6Al-4V employed as a raw material. Considering the unit volume of 1 dm^3, the deposition rate of 0.5 kg/h (provided by machine specification - see annex 1) and admitting that the density of Ti-6Al-4V is 4.43 kg/dm^3 (see annex 2), the quantity consumed per unit volume can set a value of 4.43 kg, as presented in equation 12.

$$mass = \frac{density}{volume} = \frac{\rho}{V} = \frac{4.43\ kg/dm^3}{1\ dm^3} = 4.43\ kg \qquad (12)$$

Then, dividing the calculated mass by the machine deposition rate, it results in a build time (t_b) of approximately 8.86 h, for the presented case (see equation 13). Taking into account the defined conditions, this value is expected to be the minimum possible value. However, it may suffer changes due to factors such as different laser efficiency, scan strategy or section area. Depending on these variables and considering a safety margin, this value could be increased by around 20%.

$$t_b = \frac{mass}{deposition\ rate} = \frac{4.43\ kg}{0.5\ kg/h} = 8.86\ h \qquad (13)$$

3.3.3.2 Machine Hourly Rate

The machine hourly rate is a considerable element inside the build costs. This is fundamentally the sum of direct costs and indirect costs, as can be seen schematized in Figure 33. This variable is given by the following equation:

$$machine\ hourly\ rate = direct\ costs + indirect\ costs \qquad (14)$$

The direct costs are those related to electrical energy and gas costs.

$$direct\ costs = electrical\ energy\ cost + gas\ cost \qquad (15)$$

The electrical energy costs can be simply estimated by calculating the product of the electrical energy consumption by its price, as:

$$electrical\ energy\ cost = consumption \times price \tag{16}$$

The electrical energy consumption can be calculated in terms of the energy consumption rate, considering the kilowatt hours (kWh) consumed per kilogram of deposited mass. The Energy Consumption Rate (ECR) is simply given by the following formula:

$$ECR = \frac{electrical\ energy\ consumed}{mass\ deposited} \tag{17}$$

Example:

As stated by Morrow et al. [57], it is possible to estimate the electrical energy consumption of a DED process. He studied the energy consumption and the environmental impact of a powder-based AM system. This author reported a mean power consumption of 61 kW and found this type of technology having an ECR of 2141.11 kWh/kg. This value includes the energy of a 6 kW CO^2 laser, a CNC worktable, chillers, powder feeder motors, a computerized control system and two stress relief treatments that were performed on the tool to prevent it from cracking, being also these treatments performed in a furnace rated at 13 kW. Therefore, considering 1 kg of material deployed and an ECR of 2141.11 kWh/kg:

$$electrical\ energy\ consumption = 2141.11\ kWh/kg \tag{18}$$

Furthermore, considering the price of 0.12 €/kWh for the industrial electricity in Italy (see annex 3), the cost for the electrical energy results in 256.93 € per unit of mass, as shown by:

$$\begin{aligned} electrical\ energy\ costs = {} & 2141.11\ kWh/kg \times 0.12€/kWh \\ & = 256.93€/kg \end{aligned} \tag{19}$$

The result of costs for electrical energy, shown in equation 19, demonstrates a value considerably high due to the power needed for the 6 kW CO^2 laser and all the respective used equipment.

As an alternative, another estimation of costs can be made with a more conservative situation.

Example:

The research objectives of Wilson et al. [72] included the effectiveness of laser direct deposition and the respective energy and environmental impacts. The experiments were carried out on an Optomec LENS® 750, equipped with an IPG fiber laser, with a power capacity of 500 W and a maximum work envelope of 300x300x300 mm^3. The results demonstrated this technology having an ECR of 292 kWh/kg. Thus, considering the DED system LENS® 850-R from Optomec, taken as reference (see section 3.3.3.1) and its IPG fiber laser of 1000 W (see annex 1), the ECR adopted in this case is 584 kWh/kg (292 kWh/kg x 2, by adjusting the 1000 W power to 2x500 W). Then, assuming 1 kg of material deployed and this ECR of 584 kWh/kg:

$$electrical\ energy\ consumption = 584\ kWh/kg \tag{20}$$

Then, considering again the price for the industrial electricity in Italy (annex 3), the cost for the electrical energy results in a value of 70.08 € per kilogram, as presented in equation 21.

$$\begin{aligned} electrical\ energy\ costs = &\ 584\ kWh/kg \times 0.12€/kWh \\ &= 70.08€/kg \end{aligned} \tag{21}$$

As for direct costs related with the gas consumption, they are further detailed in section 3.3.3.5.

On the other hand, the indirect costs include the machine, all the DED equipment, as well as the ordinary maintenance and production overheads. These costs are represented in equation 22.

$$\begin{aligned} &indirect\ costs \\ &\quad = machine\ cost + equipment\ maintenance \\ &\quad + labor\ cost + administrative\ cost \end{aligned} \tag{22}$$

Example:

The indirect cost may be quantified at around 700 000 €, being the investment cost for a DED machine. Then, according to Lindemann et al. [71] the machine utilization can be considered 5 years based on its standard depreciation time. In one year the machine utilization is circa 5000 h and hereupon the total machine utilization, considering the 5 years, can be assumed as 25 000 h, just as shown in equation 23.

$$machine\ utilization = 5\ years \times 5000\ h = 25\ 000\ h \tag{23}$$

Consequently, dividing the indirect costs (700 000 €) by the total machine utilization (25 000 h) a value of 28 €/h is obtained, as shown in equation 24.

$$machine\ hourly\ rate = \frac{price}{utilization} = \frac{700\ 000\ €}{25\ 000\ h} = 28\ €/h \tag{24}$$

Furthermore, the production overheads, which contemplates the supporting equipment, the facility rent, the software license and the total labor, is also considered and it can be estimated as a percentage of 15% of the machine hourly rate calculated previously (see equation 25). Therefore, the total machine hourly rate will give a value of 32.2 €/h.

$$total\ machine\ hourly\ rate = 28\ \times (1 + 0.15) = 32.2\ €/h \tag{25}$$

3.3.3.3 Small Maintenance Cost

Fixed costs may include also the costs related with small maintenance (C_{sm}). This type of maintenance deals with every operation necessary to maintain the machine with an adequate and proper functioning, which does not require a machine expert. This may include the operator cost and the replacement parts cost, such as the nozzle. Therefore, the small maintenance cost depends on the hourly labor cost (C_{labor}), replacement parts cost (C_{rp}), as well as the time necessary to execute this type of maintenance (t_{sm}). Accordingly, the small maintenance cost is given by:

$$C_{sm} = t_{sm} \times C_{labor} + C_{rp} \tag{26}$$

This small maintenance is carried out in a systematic way within a fixed period. Thus, the time between small maintenance (TBSM) is a variable considered to estimate the costs, as well as the build time (t_b). These components can be represented by the following equation:

$$t_b \div TBSM = C_{sm,job}\ \div C_{sm} \tag{27}$$

Hence, the small maintenance costs per job ($C_{sm,job}$) are given by:

$$C_{sm,job} = C_{sm} \times \frac{t_b}{TBSM} \tag{28}$$

3.3.3.4 Labor Cost

Concerning the labor cost, it should be certainly considered in those activities which require an experienced operator to monitor the machine. The building process is mainly automatic, although the operation process monitoring is still required since the online process monitoring is done at earlier phases. Thus, to evaluate the labor costs related to the DED process, it could be settled a factor for operator occupation of 5%, which is the percentage of time the operator is involved and working with the machine. In order to estimate the hourly wage cost of an operator, Atzeni et al. [44] considered a manufacturing plant located in Western Europe and estimated a value ranging from 20.00 to 30.00 €, according to the required skills. The labor cost per job is determined by the hourly labor cost (C_{labor}), the build time (t_b) as well as the percentage of operator working time (p) and it can be given by the following equation:

$$C_{labor,job} = C_{labor} \times t_b \times p \quad (29)$$

3.3.3.5 Gas Cost

The gas cost includes both variable and fixed costs. The variable gas costs are typically dependent on the gas consumption.

Example:

Based on a case study presented by Kerbrat et al. [73], it is feasible to estimate the gas consumption of DED process. This study aimed to evaluate the environmental impact of a DED technology. The results regarding the gas consumption were 176 l for carrying gas and 330 l for the conforming gas, being the observed manufacturing time as 4395 s. Thus, a value of 506 l comes out for the total gas consumption and 73.25 min for the manufacturing time, which gives the gas consumption per unit of time, as:

$$total\ gas\ consumption = \frac{506\ l}{73.25\ min} = 6.9\ l/min \quad (30)$$

Then, converting this value into liters per hour:

$$total\ gas\ consumption = 6.9\ l/min \times 60 = 414\ l/h \quad (31)$$

Finally, the total gas consumption in cubic meters per hour is:

$$total\ gas\ consumption = 414\ l/h \times 10^{-3} = 0.4\ m^3/h \quad (32)$$

As for fixed gas costs, these are costs related with gas prices.

Example:

To estimate fixed gas costs, it has been considered a quotation price for DED inert gases from a leading Italian chemical group named SIAD specialized in industrial gases (see annex 4). The type of inert gas chosen for current estimation was argon, since it is the most common gas, used in DED systems. So, according to this quotation, the price for 140.8 m^3 of argon is 1056 €, which results in a price of 7.5 €/m^3. The volume of Argon gas consumed for the DED process can be calculated multiplying the build time (t_b), per 1 dm^3 unit volume (equation 13), by the total gas consumption (equation 32), as shown in the following equation:

$$volume\ gas\ consumed = 8.86\ h \times 0.4\ m^3/h = 3.5\ m^3 \tag{33}$$

Hence, the gas consumption cost per job per 1 dm^3 unit volume is given by:

$$gas\ comsuption\ cost = 7.5\ €/m^3 \times 3.5\ m^3 = 26\ €/dm^3 \tag{34}$$

Additionally, according to the price quotation mentioned before, the argon gas supplying requires a maintenance cost of 700 € per year (see annex 4). Thus, considering the machine utilization per year of 5000 h, this cost per hour is given by:

$$gas\ maintenance\ cost = \frac{700\ €}{5000\ h} = 0.14\ €/h \tag{35}$$

Then, the argon gas maintenance cost per job can be obtained by multiplying the gas maintenance cost calculated by equation 35 with the build time (given by equation 13), as expressed in the following equation:

$$gas\ maintenance\ cost\ per\ job = 8.86\ h \times 0.14€/h = 1.24\ € \tag{36}$$

3.3.4 Thermal Treatment

The thermal treatment is still part of the manufacturing stage, as illustrated in Figure 32. As many AM methods, the DED process requires a subsequent heat treatment in order to reduce internal stresses, increase density and develop the final shape, finishing and, most importantly, microstructural phases, resulting in the desired physical and mechanical properties [11, 62]. This operation is performed with industrial furnaces as the one shown in Figure 34.

Figure 34 - Hot-wall retort furnace NRA 150/09 from the German brand Nabertherm GmbH [74].

The costs related to thermal operations are based on a standard thermal treatment, which means they have a fixed cost, according to the number (and size) of parts (N) in the same treatment. Thus, the thermal treatment cost per part ($C_{tt,part}$) can be simply expressed as:

$$C_{tt,part} = \frac{C_{tt}}{N} \tag{37}$$

3.3.5 Finishing Processes

The finishing processes are operations such as machining or manual polishing which are part of the finishing stage in a DED process chain. These processes are often necessary in order to impart the desired geometric features, surface finish and dimensional accuracy characteristics to manufactured parts. The machining process is the most common finishing process adopted and for this reason, its associated costs are those being considered in this section. Typically, the finishing processes cost consist in three items: the machining cost (C_m), the cost of setting up for machining (C_s) and the tooling cost (C_t), as shown in the equation 38.

$$C_f = C_m + C_s + C_t \tag{38}$$

The machining cost is dependent on the machining time (t_m), the labor cost (C_{labor}) and the overheads charges (C_o) of the machine, including depreciation, maintenance, indirect labor and related. This machining cost is given by the following equation:

$$C_m = t_m(C_{labor} + C_o) \tag{39}$$

The machining time (t_m) can be estimated by the volume of material to be removed from the manufactured part, also labeled volume allowance (V_a), and the material removal rate (MRR). These variables are normally depending on the machine adopted and on the process parameters. The machining time is, thus, given by:

$$t_m = \frac{V_a}{MRR} = \frac{V_a}{\frac{volume}{time}} \tag{40}$$

The setting up for the machining involves mounting and changing tools, such as cutters, jigs and fixtures, and preparing for the particular operation. The setting up cost (C_s) is simply determined by the setting up time ($t_{set\text{-}up}$), the labor cost (C_{labor}), the overheads charges (C_o), as well as the number of parts machined with the same set-up (N), as expressed by the following equation:

$$C_s = \frac{t_{set-up} \times (C_{labor} + C_o)}{N} \quad (41)$$

Finally, the tooling cost (C_t) can take different forms depending on the application but it generally includes factors such as tool changing, insert indexing, regrinding and depreciation of the cutter or insert. According to Kalpakjian et al. [75], this cost involves the number of parts machined per insert (N_i), the number of parts that can be produced per insert face (N_f), the time required to change the insert (t_c), the time required to index the insert (t_i), the depreciation of the insert (D_i), the labor cost (C_{labor}) and the overheads charges (C_o). The author deduced a formula to calculate the tooling cost expressed by:

$$C_t = \frac{1}{N_i}[t_c(C_{labor} + C_o) + D_i] + \frac{1}{N_f}[t_i(C_{labor} + C_o)] \quad (42)$$

The finishing cost is highly dependent on the part geometry. To estimate this type of costs it would be necessary to carry out a practical case, due to such part geometry dependence.

3.3.6 Verification and Documentation

The verification and documentation are within the final stage of the DED process chain, which is labeled Quality Control, as illustrated in Figure 32. These ultimate steps involve qualifying and measuring every produced part to verify if the product requirements are met, such as geometrical or dimensional tolerances This operation is commonly performed with a precise measuring system, Coordinate Measuring Machine (CMM), as the one shown in Figure 35. This device measures the geometry of physical objects by determining coordinates of points on a workpiece surface.

Figure 35 - Coordinate Measuring Machine CRYSTA-Apex S 9106 developed by the Japanese company Mitutoyo [76].

The cost related with this operation of quality control involves the CMM device cost (C_{CMM}), the labor cost to operate the CMM device ($C_{labor\ CMM}$) and the time of this operation (t_{CMM}), as shown in the following equation:

$$C_{qc} = (C_{CMM} + C_{labor\ CMM}) \times t_{CMM} \quad (43)$$

3.4 Results and Discussion

In this section it is explained the basis of the cost analysis performed in the previous section and presented an evaluation and interpretation of the results obtained.

In this study, a cost model has been developed using a spreadsheet and an automated procedure. The model is able to perform a cost estimation analysis using a precise and conclusive methodology. The developed cost model was based on the estimation of all the costs for each DED process step (see annex 5). The main variables contemplated in the model were the consumed mass of material (kg), the machine deposition rate (kg/h) and the process build time (hours). Table 4 presents a breakdown of the main variables used to develop the cost model.

Table 4 – Main variables used in the cost model.

Activity/Element	Cost
Machine purchase	700 000 €
Machine overall utilization	25 000 h
Labor cost	25 €/h
Material price (Ti-6Al-4V)	230 €/kg
Electricity price	0.12 €/Kwh
Gas price	7.5 €/m^3
Thermal treatment	35 €/part
Coordinate Measuring Machine (CMM) rate	45 €/h
CMM labor cost	20 €/h

Most of these assumptions were explained in detail at section 3.3. The material and the thermal treatment prices were defined based on the information provided by an expert from LPW Technology company [77]. The considered material was the titanium alloy Ti-6Al-4V. The CMM rate and labor cost were determined based on information found in literature [78].

Hereupon, considering the calculations of the costs for each process step in the cost model, it has been feasible an estimation of final cost for a DED technology by setting or defining the main variables mentioned for current cost model.

The main variables defined for the first test using the cost model were the following: 0.5 kg/h for the machine deposition rate, which is the deposition rate of the machine taken into consideration for this study - Optomec LENS® 850-R (see annex 1), 1 kg of mass of material consumed and consequently a process build time of 2 hours. The corresponding results show that the prime contributors to the costs were the material, the machine preparation, the electrical energy and the machine. The material was the most expensive component, valuing 299 €, then the machine preparation was the most expensive activity valuing 166 €, followed by the electrical energy which reached a value of 70 € and the fourth position was the machine cost with a resulting value of 64 €. These costs elements and the remaining ones can be seen in Figure 36.

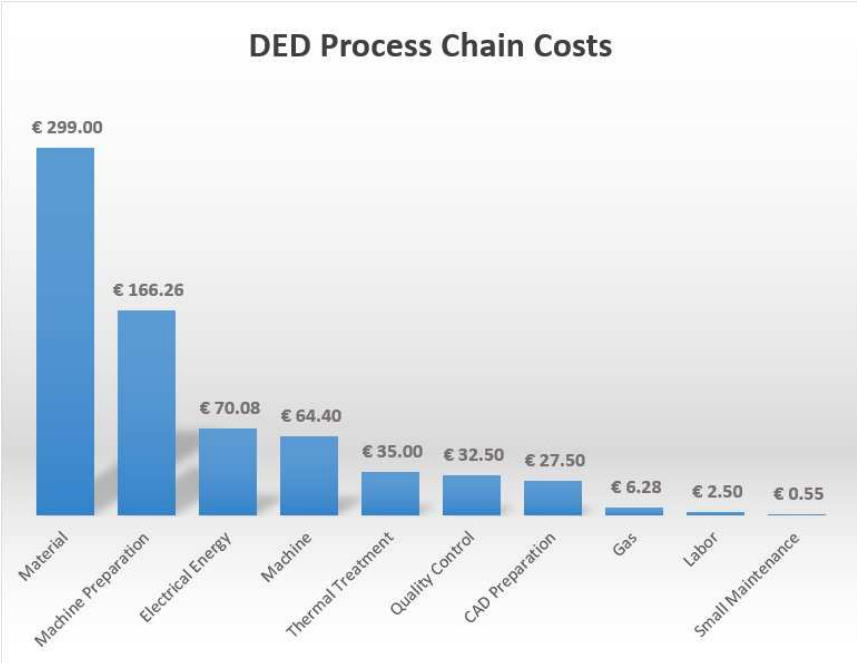


Figure 36 - The cost structure of a DED process employing a mass of 1 kg.

The total cost of a DED process in this first test, with 1 kg of mass of consumed material, settled a value of 704,07 €. The four prime mentioned contributors represent an amount of around 85% of the total cost, as shown in Figure 37.

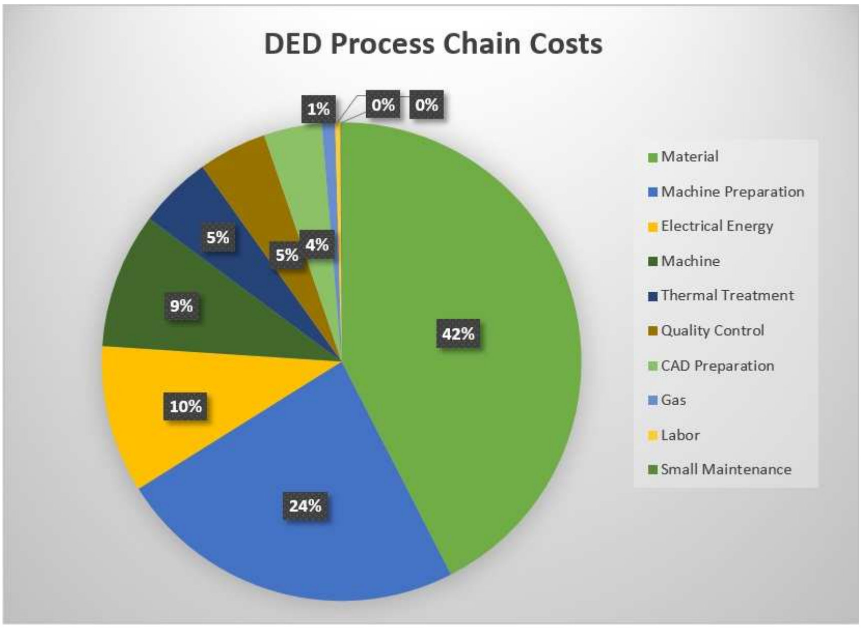


Figure 37 - The cost percentages of a DED process employing a mass of 1 kg.

The major cost driver was the material cost, which represents 42% of the total cost. The material cost consists basically in the acquisition of the metal powder, which is frequently used as raw material in a DED process. Currently, the metal powder industry is unable to benefit from economies of scale and powder costs are considerably high. In the future, it is expectable the metal powder demand to increase dramatically allowing producers to set more competitive prices [79]. The designer can also have an important role in order to reduce costs concerning the material. The volume of the DED part will decrease constantly as the designer is capable of producing independently of manufacturing restrictions.

The second largest cost driver was the machine preparation (24%). While the build process itself is nearly labor-free, the build preparation is not automated. In fact, the machine preparation, as long as the data preparation, are the main activities in which the labor costs are considerable, because it requires a skilled and experienced technician. Knowledge is necessary to orient the parts in the building chamber and to develop the CAD file [71]. Still, the time spent in this preparation stage is quite considerable, which has an effect on the involved costs.

These two cost drivers were followed by the electrical energy cost (10%). This cost is directly dependent on the power consumption of the high-power laser, which means that higher the power consumption, higher the cost. This confirmation was possible to understand when estimating the electrical energy costs (see section 3.3.3.2). By adopting a 6 kW CO^2 laser, as well as the respective equipment, it would need a power consumption almost four times higher than a 1 kW IPG fiber laser. The high-power laser is the main electrical energy consumption element and this energy consumption should be also taken into account when it comes to environmental considerations. In fact, green manufacturing is defined as the primary step towards sustainable development. Thus, comparing the electrical energy consumption of the DED process with similar AM processes, it can be noticed that DED is unfavorable at this point. As it can be seen in Table 5 the Energy Consumption Rate (ECR) values are considerably low in contrast with the ECR determined for a DED technology. Wilson et al. [72] carried out his experiments in the Optomec LENS® 750 system equipped with a 500 W IPG fiber laser and obtained a value for ECR of 292 kWh/kg.

Table 5 – Energy Consumption Rates reported in literature on metallic AM.

Reference	**Process**	**System and material grade**	**Energy Consumption Rate (ECR)**
Wilson et al. [72]	Directed Energy Deposition	Optomec LENS® 750, Stainless steel 316L	292 kWh/kg
Baumers et al. [80]	Electron Beam Melting	Arcam A1, Ti-6Al-4V	17-49 kWh/kg
Baumers et al. [80]	Selective Laser Melting	MTT SLM 250, Stainless steel SAE 316L	31-38 kWh/kg
Baumers et al. [81]	Selective Laser Melting	MTT SLM 250, Stainless steel 316L	23-29 kWh/kg
Baumers et al. [81]	Selective Laser Melting	Concept Laser M3 Linear, Stainless steel 316L	118-163 kWh/kg

The fourth most critical factor found, regarding DED production costs, was the machine (9%). As the machine investment cost is an influential factor in the cost of a DED part, the utilization rate should be quite accurate. As machine time is the largest price cause, all the means to decrease the time also decrease the cost proportionately (e.g. by reducing the material employed, when in the product design phase). The designer should master the manufacturing method in detail, since its properties and limitations are considerably different from conventional manufacturing. This approach is known as Design For Manufacturing and Assembly - DFMA [82].

3.4.1 Material Quantity Analysis

In order to determine the influence on costs of the consumed mass of material, three more tests were performed and results were examined by changing this variable. In this analysis, the machine deposition rate has been kept the same (0.5 kg/h) but it has been tested 5, 10 and 20 kg for the mass of consumed material, which consequently got the build time of 10, 20 and 40 h, respectively.

From these experiments, it is feasible to conclude that some costs are increased in function of the mass of the employed material, while other costs remain constant. As observed in Figure 38, the material cost is strictly contingent on the mass of consumed material, in other words, the material mass is the central variable of material costs. Also, the electrical energy cost increases in function of the mass of the raw material usage. Additionally, the machine, gas, labor and small maintenance costs are dependent on the build time, which is the main factor of their corresponding increases. The machine preparation, thermal treatment, quality control and CAD preparation costs keep constant and the mass of consumed material does not actuate on these costs.

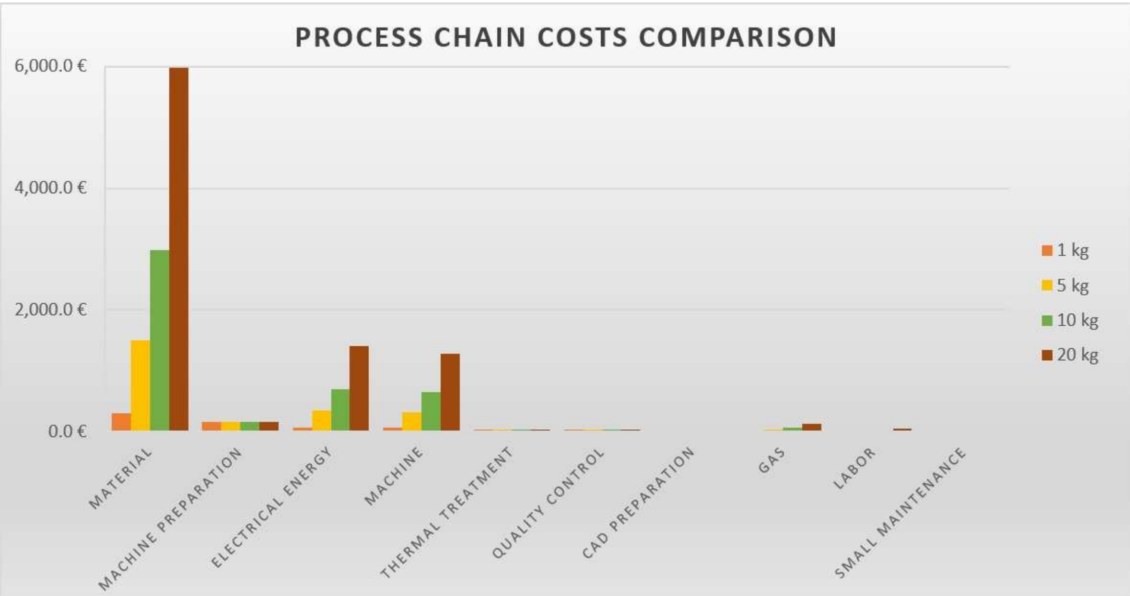


Figure 38 - The cost structure of a DED process employing a mass of 1, 5, 10 and 20 kg.

The diagram shown in Figure 39 gives a deep perception of the influence of the mass of consumed material on the costs. The diagram presents the weight for each process step on the total cost, employing distinct figures of material mass. The machine and electrical energy costs are the two cost element percentages which remain untouchables with the increase of the material mass. The material and machine costs are two cost elements for which the cost percentage behave in opposite manner. The material cost percentage increase in function of the increase of the mass of the consumed material and the machine preparation tend to get lower. Additionally, it can also be understood from this diagram that the major cost drivers are continually the material, the machine preparation, the electrical energy and the machine.

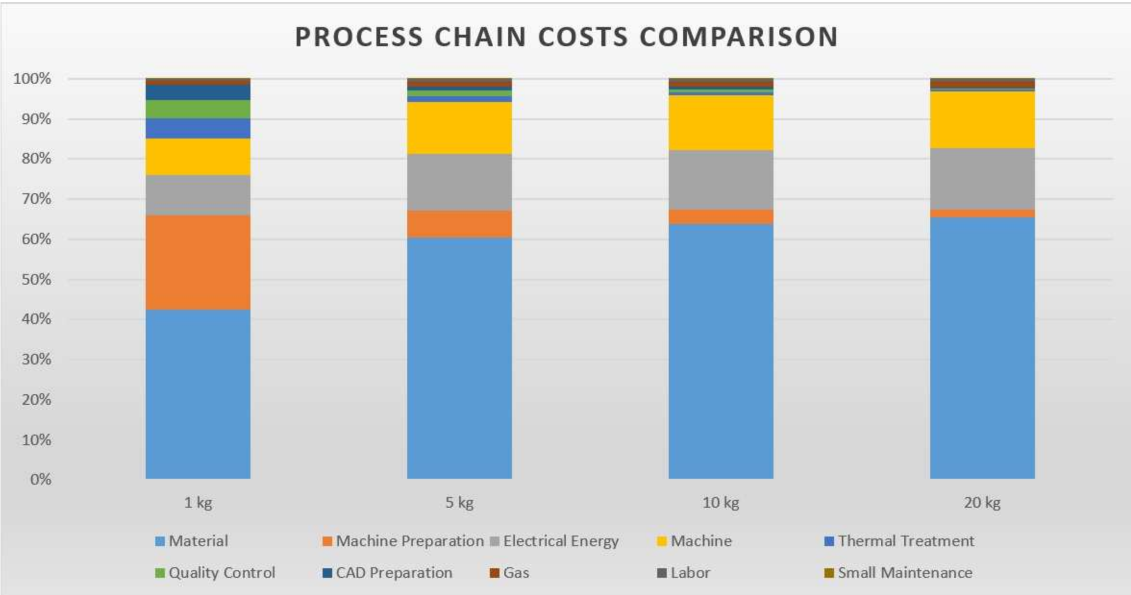


Figure 39 - The percentage cost structure of a DED process employing a mass of 1, 5, 10 and 20 kg.

Figure 40 also shows the material cost as being the main cost driver. The chart presented in Figure 40 displays the trend which results when increasing the mass of employed material. The total cost resulting from using 5 kg of raw material is more than twice higher than the total cost when adopting 1 kg of material. Then, analyzing the total costs from 5, 10 and 20 kg it is possible to observe that the cost from 10 kg is approximately twice higher than the cost from 5 kg and the same happens when comparing the results from the costs of 10 and 20 kg. This means that the total cost in function of the mass of used material is basically linear when employing high quantities of mass. Thus, it is feasible to conclude that DED technology is profitable for building parts that require big amount of material and so it is less favorable for producing small parts.

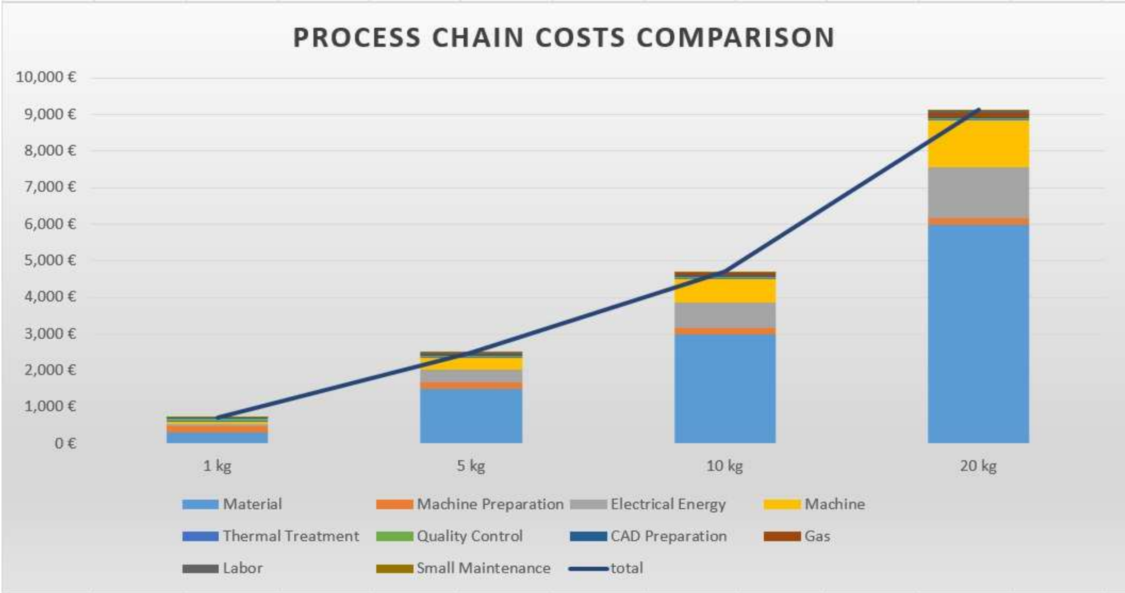


Figure 40 - The cost structure of a DED process employing a mass of 1, 5, 10 and 20 kg.

3.4.2 Sensitivity Analysis for material and machine costs

The present study allowed the determination of the main cost drivers for a DED process. Two of those cost identified elements were the material and the machine cost.

Therefore, in order to find out the impact of these two elements on the total cost, a fundamental sensitivity analysis has been performed, so that a quantification and evaluation on how much each element is relevant and contributing to the costs, in addition to corresponding input variations. The analyzed scenarios were defined by considering 1 and 5 kg for material mass, since those are related with the most applied particular results, besides being possible to confirm the previous understanding of linear behavior.

Accordingly, the variations of tested variables were the following:

- reducing 10% in machine cost;
- adding 10% in machine cost;
- reducing 10% in material cost;
- reducing 10% in material cost and machine cost;
- reducing 10% in material cost and adding 10% in machine cost.

Beginning with the analysis performed with the results from 1 kg scenario, the most noticeable variation occurred when decreasing in 10% both material and machine cost, resulting in a value of around 5% less in comparison with the reference. The other variation was made in the machine cost resulting in a trivial increase of circa 1%. With these effects, it can be concluded that the material and machine cost are two elements having great influence on the final cost. These results are presented in Figure 41.

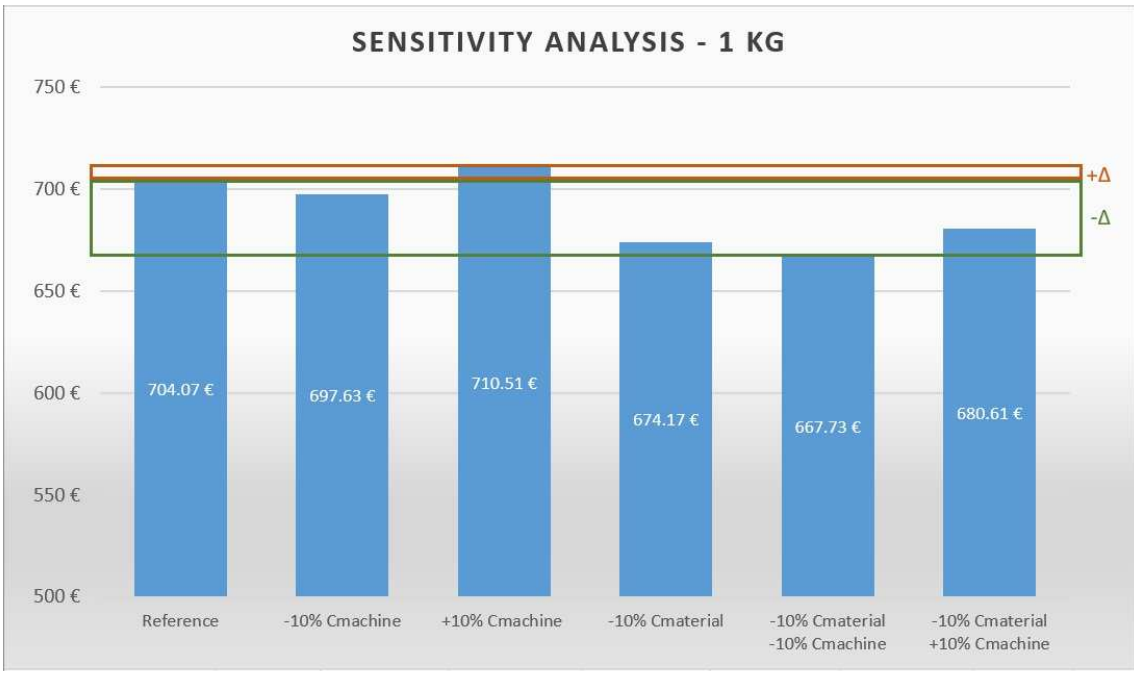


Figure 41 – Results from the sensitivity analysis for 1 kg scenario.

Concerning the scenario with a mass of 5 kg consumed material, the outcomes from the sensitivity analysis were identical. When varying the material and machine cost there was a decrease of around 7% in the total cost compared with the reference (2475.31€). The change in the machine cost resulted in an increase of around 1%, as it can be seen in Figure 42. Once again, it can be concluded that both machine and material costs have a strong impact and they can completely affect the total cost.

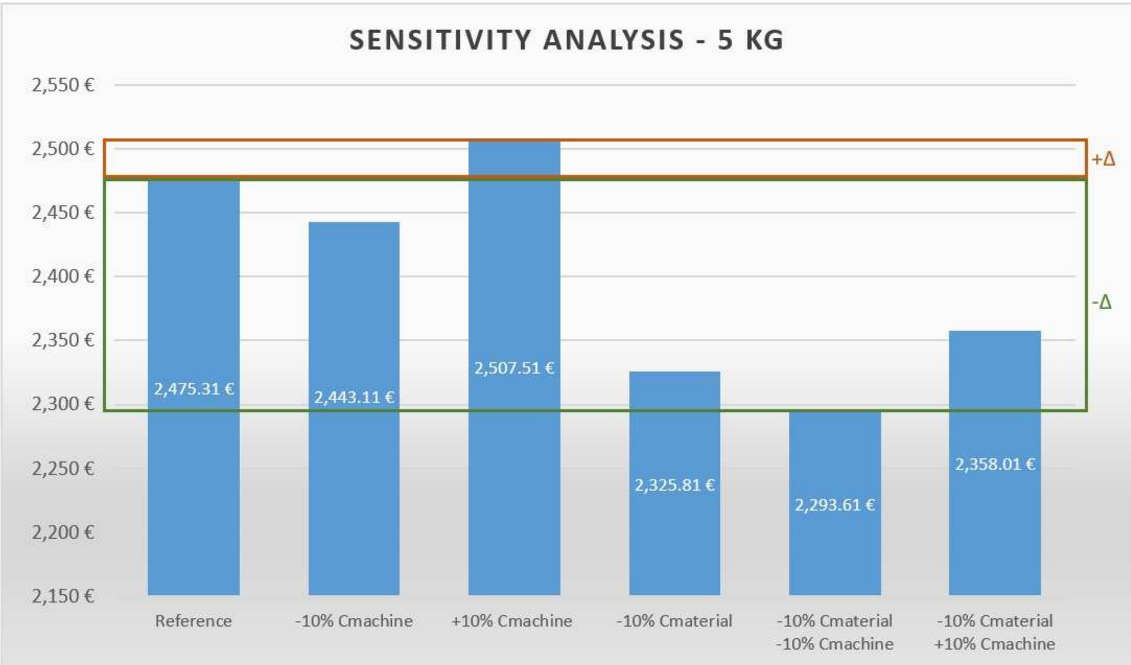


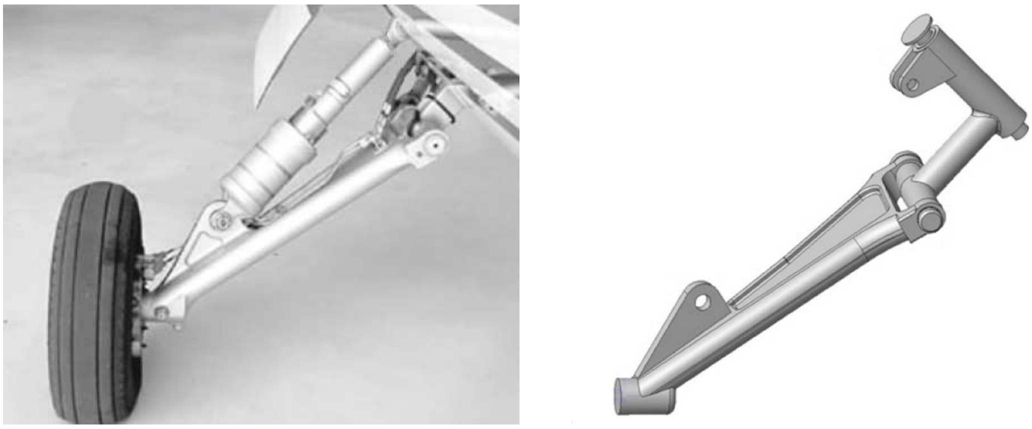
Figure 42 - Results from the sensitivity analysis for 5 kg scenario.

3.4.3 Case study and comparison with literature

The present cost estimation analysis was one of the first studies about the economics of DED process. The empirical results on cost performance obtained in previous sections for current study indicate that adoption of DED process seems highly interesting. For this reason, it will be important that the results obtained shall be contextualized with the literature on metallic Additive Manufacturing.

Therefore, a case study has been selected from literature based on the work of Atzeni et al. [44] and corresponding cost results will be compared with different cost results obtained by different authors. This selected case study and corresponding developed cost model was applied for Direct Metal Laser Sintering (DMLS) technique, which is a Powder Bed Fusion technique and uses a high-power laser beam as focused heat source, employing also metal powder likewise DED process.

The case study consisted on the manufacturing of an aeronautical component, shown in Figure 43. This component is the main landing gear of the Italian aircraft P180 Avant II by Piaggio Aero Industries S.p.A. and the redesigned part is presented in Figure 43 (b).



(a) (b)

Figure 43 – (a) Aeronautical component used in the case study; (b) redesigned part [44].

Regarding the technical aspects, the part overall dimensions are 70×210×70 (mm) (width×length×height) and the material is an aluminum alloy – AlSi10Mg. The cost model includes four parts per job and the mass of material per part is 0.178 kg. Therefore, in order to compare the results obtained with the research made by Atzeni et al. [44], it has been settled the same value of the mass of material (0.178 kg) for the model created in the present study (see annex 6). Thus, according to current developed cost model, the estimated total cost would be 340.08 €. Accordingly, also considering the system Optomec LENS® 850-R and the Ti-6Al-4V alloy as raw material with a corresponding density of 4.43 kg/dm^3, the calculation for obtaining the specific cost estimation can be done with the following equation:

$$Specific\ cost\ estimation = \frac{340.08\ € \times 0.00443\ kg/cm^3}{0.178\ kg} = 8.46\ €/cm^3 \quad (44)$$

The head-on comparison, made between the results obtained from the cost model for the DED process performed in the present work and the results obtained by the cost model for the DMLS process made by Atzeni et al. [44], is presented in Table 6.

Table 6 – Specific cost estimation comparison for the case study proposed by Atzeni et al. [44].

Reference	System and material grade	Notable cost model elements	Specific cost estimation
Present study	Optomec LENS® 850-R system, Ti-6Al-4V	• Single-part build, single geometry • Includes pre- and post-processing (heat treatment)	8.46 €/cm^3
Atzeni et al. [44]	Laser-sintering system EOSINT M270, AlSi10Mg	• Multi-part build, single geometry • Includes pre- and post-processing (heat treatment)	7.92 €/cm^3

Previous results can further be compared with other studies in literature. By considering specific cost outcomes for similar metallic powder bed fusion systems [83], it is shown in Table 7 the results of cost estimations from different authors.

Table 7 – Specific cost estimations comparison with the literature on metallic AM (adapted from Baumers [83]).

Reference	System and material grade	Notable cost model elements	Specific cost estimation
Present study	Optomec LENS® 850-R system, Ti-6Al-4V	• Single-part build, single geometry • Includes pre- and post-processing (heat treatment)	8.46 €/cm^3
Atzeni et al. [44]	Laser-sintering system EOSINT M270, AlSi10Mg	• Multi-part build, single geometry • Includes pre- and post-processing (heat treatment)	7.92 €/cm^3
Baumers et al. [84]	Laser-sintering system EOSINT M270, Stainless steel 316L	• Multi-part build, multiple geometries • Including wire erosion to separate parts from build platform	7.03 €/cm^3
Rickenbacher et al. [85]	Unspecified selective laser melting system, unspecified material grade	• Multi-material build, single geometry • Includes pre- and post-processing, including wire erosion to separate substrate	28.20 to 66.75 €/cm^3

Piili et al. [82]	Unspecified selective laser melting prototype system, Stainless steel	• Multi-part build, single geometry	8.25 €/cm^3
Baumers et al. [83]	Laser-sintering system EOSINT M270, Stainless steel 17-4PH	• Mixed build	6.70 €/cm^3
		• Single-part build	8.25 €/cm^3

As seen, the specific cost estimation reached with the current developed cost model (8.46 €/cm^3) is identical to those estimated by other authors. The exception is Rickenbacher et al. [85] cost estimation, who considers a very high machine rate of 90 €/h, which is approximately three times more than the machine cost in current research (32.2 €/h).

Therefore, costs obtained for DED and its comparison with other metallic AM processes show that this technology presents cost effectiveness and represents an adequate possibility for being used. However, further studies should be performed and a practical test case is needed in order to validate developed model and its results.

CONCLUSIONS

4 CONCLUSIONS AND FUTURE WORK

4.1 CONCLUSIONS

The Additive Manufacturing (AM) technologies are changing the possibilities of manufacturing and having a great impact on the industry, due to their ability for being cost-effective, efficient and environmentally friendly. This perspective is illustrated by the McKinsey Global Institute, which named AM as one of the twelve disruptive technologies that will transform the business and the global economy by 2025.

In the present work, a cost model has been proposed and applied to quantify the cost-effectiveness of a Directed Energy Deposition (DED) process. This model mainly represents theoretical aspects and it has been a result of intense literature research to complete all data for the application scenario profiles. The cost model represents one of the firsts analysis and evaluation of the costs involving the full process chain of the DED process.

The results obtained from the present study suggest that DED process adoption seems highly interesting for building parts that require a reasonable quantity of material and is less suitable for producing small parts.

The performed cost analysis showed that the prime contributors to the costs of a DED process are the material, the machine preparation, the electrical energy and the machine. The material cost is the highest one followed by the machine preparation, although the machine preparation does not vary according to mass of material consumed, being a fixed cost. A sensitivity analysis also showed that both machine and material cost have a strong impact and they can completely affect the total cost of a DED process.

A case study has been selected from literature and results showed comparable costs per volume of material, between current DED cost evaluation and selected DLMS process presented, in such study.

Developed cost model has been also contextualized in the literature by comparing specific cost outcomes for similar metallic powder AM systems and different cost approaches by different authors. Such comparison showed that current model can estimate identical values for specific costs outcomes, although the considerations, included costs and methodologies are different according to each research group or author.

4.2 FUTURE WORK

The analysis and developments performed under this dissertation will need to be complemented by accomplishing a practical case, in order to estimate and validate all the costs along the DED process chain, mainly regarding the finishing processes costs, which are highly dependent on the geometry of the part to be produced.

Further work will also need to focus on systematically expanding the DED cost model for other materials, other deposition rates, multi-part build and multiple geometries. It is envisioned that this will establish the limits of the cost-effectiveness of the DED process to enable optimal process selection and potentially highlight new areas of opportunity.

REFERENCES

5 References

1. Costabile, G., et al., *Cost models of additive manufacturing: A literature review.* International Journal of Industrial Engineering Computations, 2017. **8**(2): p. 263-283.

2. Lindemann, C., et al., *Towards a sustainable and economic selection of part candidates for additive manufacturing.* Rapid Prototyping Journal, 2015. **21**(2): p. 216-227.

3. Rejeski, D., F. Zhao, and Y. Huang, *Research needs and recommendations on environmental implications of additive manufacturing.* Additive Manufacturing, 2017.

4. ASTM, *F2792. 2012. standard terminology for additive manufacturing technologies*, in *ASTM F2792-10e1*. 2012.

5. Calignano, F., et al., *Overview on Additive Manufacturing Technologies.* Proceedings of the IEEE, 2017. **105**(4): p. 593-612.

6. Schmidt, M., et al., *Laser based additive manufacturing in industry and academia.* CIRP Annals, 2017. **66**(2): p. 561-583.

7. Algardh, J., et al., *State-of-the-art for Additive Manufacturing of Metals*. 2017: Sweden.

8. ISO/ASTM, *Additive manufacturing - General principles - Terminology (ISO/ASTM 52900:2015)*. 2017.

9. DebRoy, T., et al., *Additive manufacturing of metallic components – Process, structure and properties.* Progress in Materials Science, 2018. **92**: p. 112-224.

10. Thomas, D.S. and S.W. Gilbert, *Costs and cost effectiveness of additive manufacturing.* NIST Special Publication, 2014. **1176**: p. 12.

11. Gibson, I., D.W. Rosen, and B. Stucker, *Additive Manufacturing Technologies*. 2010: Springer.

12. Campbell, T., et al., *Could 3D printing change the world.* Technologies, Potential, and Implications of Additive Manufacturing, Atlantic Council, Washington, DC, 2011.

13. Cotteleer, M. and J. Joyce, *3D opportunity: Additive manufacturing paths to performance, innovation, and growth.* Deloitte Review, 2014. **14**: p. 5-19.

14. Thompson, M.K., et al., *Design for Additive Manufacturing: Trends, opportunities, considerations, and constraints.* CIRP annals, 2016. **65**(2): p. 737-760.

15. 3DSystems. *What is an STL file?* 2018 February, 2018]; Available from: http://www.3dsystems.com/quickparts/learning-center/what-is-stl-file.

16. Materialise. *The Most Powerful Data Preparation Software*. 2018 February, 2018]; Available from: http://www.materialise.com/en/software/magics.

17. Schmid, P.D.-I.H.-J. and D.-I.E. Klemp, *Direct Manufacturing Research Center - Annual Report 2015*. 2015.

18. Umaras, E. and M.S. Tsuzuki, *Additive Manufacturing-Considerations on Geometric Accuracy and Factors of Influence.* IFAC-PapersOnLine, 2017. **50**(1): p. 14940-14945.

19. Wohlers, T., et al., *Wohlers Report 2017 - 3D Printing and Additive Manufacturing State of the Industry*. 2017, Annual Worldwide Progress Report.

20. Grenda, E., *Printing the future: The 3D printing and rapid prototyping source book*. 2006: Castle Island Company.

21. Lipson, H., *3D Printing, Now and Beyond - Disruptive Principles and Development Episodes*, Stratasys, Editor. 2016.

22. Wile, R., *Credit Suisse: 3D Printing Is Going To Be Way Bigger Than What The 3D Printing Companies Are Saying*, in *Business Insider*. 2013.

23. Stevenson, K. *About That Hype Cycle*. 2017 March, 2018]; Available from: http://www.fabbaloo.com/blog/2017/8/2/about-that-hype-cycle.

24. Petch, M. *Gartner Releases 2017 3D Printing Hype Cycle*. 2017 March, 2018]; Available from: https://3dprintingindustry.com/news/gartner-releases-2017-3d-printing-hype-cycle-118349

25. Goldsberry, C. *Rapid change in additive-manufacturing landscape*. 2009 March, 2018]; Available from: http://www.plasticstoday.com/rapid-change-additive-manufacturing-landscape/85941459213194.

26. Huang, Y., et al., *Additive manufacturing: current state, future potential, gaps and needs, and recommendations.* Journal of Manufacturing Science and Engineering, 2015. **137**(1): p. 014001.

27. Guo, N. and M.C. Leu, *Additive manufacturing: technology, applications and research needs.* Frontiers of Mechanical Engineering, 2013. **8**(3): p. 215-243.

28. Kruth, J.-P., M.-C. Leu, and T. Nakagawa, *Progress in additive manufacturing and rapid prototyping.* Cirp Annals, 1998. **47**(2): p. 525-540.

29. 3DPrinting.com. *What is 3D Printing?* 2018 March 2018]; Available from: https://3dprinting.com/what-is-3d-printing/.

30. Bourell, D., et al., *Materials for additive manufacturing.* CIRP Annals, 2017. **66**(2): p. 659-681.

31. Miyanaji, H., et al., *Process Development of Porcelain Ceramic Material with Binder Jetting Process for Dental Applications.* JOM, 2016. **68**(3): p. 831-841.

32. Wieland, S. and F. Petzoldt, *Binder Jet 3D-Printing for Metal Additive Manufacturing: Applications and Innovative Approaches.* Ceramic Forum International DKG 93 (2016)(10/2016):E26-E30, 2016.

33. da Silva Bartolo, P.J., et al., *Innovative Developments in Design and Manufacturing: Advanced Research in Virtual and Rapid Prototyping--Proceedings of VRP4, Oct. 2009, Leiria, Portugal*. 2009: CRC Press.

34. Tsouknidas, A., *Friction induced wear of rapid prototyping generated materials: a review.* Advances in Tribology, 2011. **2011**.

35. Galati, M. and L. Iuliano, *A literature review of powder-based electron beam melting focusing on numerical simulations.* Additive Manufacturing, 2018. **19**: p. 1-20.

36. Mueller, B. and D. Kochan, *Laminated object manufacturing for rapid tooling and patternmaking in foundry industry.* Comput. Ind., 1999. **39**(1): p. 47-53.

37. Thompson, S.M., et al., *An overview of Direct Laser Deposition for additive manufacturing; Part I: Transport phenomena, modeling and diagnostics.* Additive Manufacturing, 2015. **8**: p. 36-62.

38. Shamsaei, N., et al., *An overview of Direct Laser Deposition for additive manufacturing; Part II: Mechanical behavior, process parameter optimization and control.* Additive Manufacturing, 2015. **8**: p. 12-35.

39. Karczewski, K., et al., *Fe-Al thin walls manufactured by Laser Engineered Net Shaping.* Journal of Alloys and Compounds, 2017. **696**: p. 1105-1112.

40. Barlier, C. and A. Bernard, *Fabrication additive: Du prototypage rapide à l'impression 3D*. 2015: Dunod.

41. Küpper, D., et al., *Get Ready for Industrialized Additive Manufacturing*. 2017, The Boston Consulting Group (BCG).

42. Baumers, M., et al., *The cost of additive manufacturing: machine productivity, economies of scale and technology-push.* Technological forecasting and social change, 2016. **102**: p. 193-201.

43. Marchesi, T.R., et al., *Topologically Optimized Diesel Engine Support Manufactured with Additive Manufacturing.* IFAC-PapersOnLine, 2015. **48**(3): p. 2333-2338.

44. Atzeni, E. and A. Salmi, *Economics of additive manufacturing for end-usable metal parts.* The International Journal of Advanced Manufacturing Technology, 2012. **62**(9-12): p. 1147-1155.

45. Berger, R., *Additive manufacturing: a game changer for the manufacturing industry.* Roland Berger Strategy Consultants GmbH, Munich, 2013. **1**(5.1).

46. Hopkinson, N. 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, 2003. **217**(1): p. 31-39.

47. Fera, M., et al., *A new mixed production cost allocation model for additive manufacturing (MiProCAMAM).* The International Journal of Advanced Manufacturing Technology, 2017. **92**(9-12): p. 4275-4291.

48. Alexander, P., S. Allen, and D. Dutta, *Part orientation and build cost determination in layered manufacturing.* Computer-Aided Design, 1998. **30**(5): p. 343-356.

49. ASTM, I., *Additive manufacturing - General principles - Terminology (ISO/ASTM 52900:2015)*. 2017.

50. Koike, R., et al., *Evaluation for mechanical characteristics of Inconel625–SUS316L joint produced with direct energy deposition.* Procedia Manufacturing, 2017. **14**: p. 105-110.

51. Herderick, E., *Additive manufacturing of metals: A review.* Materials Science and Technology, 2011(MS): p. 1413.

52. Marini, D., D. Cunningham, and J.R. Corney, *Near net shape manufacturing of metal: A review of approaches and their evolutions.* Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, 2017: p. 0954405417708220.

53. Caiazzo, F., *Laser-aided Directed Metal Deposition of Ni-based superalloy powder.* Optics & Laser Technology, 2018. **103**: p. 193-198.

54. Dutta, B., et al., *Additive Manufacturing by Direct Metal Deposition*. Vol. 169. 2011. 33-36.

55. Tofail, S.A., et al., *Additive manufacturing: scientific and technological challenges, market uptake and opportunities.* Materials Today, 2017.

56. Gharbi, M., et al., *Influence of various process conditions on surface finishes induced by the direct metal deposition laser technique on a Ti–6Al–4V alloy.* Journal of materials processing technology, 2013. **213**(5): p. 791-800.

57. Morrow, W., et al., *Environmental aspects of laser-based and conventional tool and die manufacturing.* Journal of Cleaner Production, 2007. **15**(10): p. 932-943.

58. Wen, S. and Y.C. Shin, *Modeling of transport phenomena during the coaxial laser direct deposition process.* Journal of Applied Physics, 2010. **108**(4): p. 044908.

59. Herzog, D., et al., *Additive manufacturing of metals.* Acta Materialia, 2016. **117**: p. 371-392.

60. Popovich, A. and V. Sufiiarov, *Metal Powder Additive Manufacturing*, in *New Trends in 3D Printing*. 2016, InTech.

61. Optomec, *LENS^{TM} 850-R Optomec Datasheet*, Optomec, Editor. 2014.

62. Frazier, W.E., *Metal Additive Manufacturing: A Review.* Journal of Materials Engineering and Performance, 2014. **23**(6): p. 1917-1928.

63. He, X. and J. Mazumder, *Transport phenomena during direct metal deposition.* Journal of Applied Physics, 2007. **101**(5): p. 053113.

64. Toyserkani, E., A. Khajepour, and S.F. Corbin, *Laser cladding*. 2004: CRC press.

65. Optomec, *LENS Component Repair Solution - Applications*, in *LENS systems - the proven solution for high-value component repair or re-work*, Optomec, Editor. 2014. p. 2.

66. Saboori, A., et al., *An Overview of Additive Manufacturing of Titanium Components by Directed Energy Deposition: Microstructure and Mechanical Properties.* Applied Sciences, 2017. **7**(9): p. 883.

67. Allen, J., *An investigation into the comparative costs of additive manufacture vs. machine from solid for aero engine parts*. 2006, ROLLS-ROYCE PLC DERBY (UNITED KINGDOM).

68. Ruffo, M., 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, 2006. **220**(9): p. 1417-1427.

69. Thomas, D., *Costs, Benefits, and Adoption of Additive Manufacturing: A Supply Chain Perspective.* The International journal, advanced manufacturing technology, 2016. **85**(5-8): p. 1857-1876.

70. Li, Y., et al., *Additive manufacturing technology in spare parts supply chain: a comparative study.* International Journal of Production Research, 2017. **55**(5): p. 1498-1515.

71. Lindemann, C., et al. *Analyzing product lifecycle costs for a better understanding of cost drivers in additive manufacturing*. in *23th Annual International Solid Freeform Fabrication Symposium–An Additive Manufacturing Conference. Austin Texas USA 6th-8th August*. 2012.

72. Wilson, J.M., et al., *Remanufacturing of turbine blades by laser direct deposition with its energy and environmental impact analysis.* Journal of Cleaner Production, 2014. **80**: p. 170-178.

73. Kerbrat, O., et al., *Environmental impact assessment studies in Additive Manufacturing*, in *Handbook of Sustainability in Additive Manufacturing*. 2016, Springer. p. 31-63.

74. Nabertherm, *Heat Treatment in Additive Manufacturing*, Nabertherm, Editor. 2018.

75. Kalpakjian, S., S.R. Schmid, and C.W. Kok, *Manufacturing Processes for Engineering Materials*. 2008: Pearson-Prentice Hall.

76. Mitutoyo. *CNC CMM, CRYSTA-Apex S 9106*. 2018 June 2018]; Available from: https://goo.gl/AjE8Qd.

77. LPW. *LPW Technology*. 2018; Available from: https://www.lpwtechnology.com/.

78. Hocken, R.J. and P.H. Pereira, *Coordinate measuring machines and systems*. 2016: CRC Press.

79. Mellor, S., L. Hao, and D. Zhang, *Additive manufacturing: A framework for implementation.* International Journal of Production Economics, 2014. **149**: p. 194-201.

80. Baumers, M., et al. *A comparative study of metallic additive manufacturing power consumption*. in *Solid freeform fabrication symposium*. 2010.

81. Baumers, M., et al., *Energy inputs to additive manufacturing: does capacity utilization matter.* Eos, 2011. **1000**(270): p. 30-40.

82. Piili, H., et al., *Cost Estimation of Laser Additive Manufacturing of Stainless Steel*. Vol. 78. 2015. 388-396.

83. Baumers, M., et al., *Informing additive manufacturing technology adoption: total cost and the impact of capacity utilisation.* International Journal of Production Research, 2017. **55**(23): p. 6957-6970.

84. Baumers, M., et al., *Transparency built-in.* Journal of Industrial Ecology, 2013. **17**(3): p. 418-431.

85. Rickenbacher, L., A. Spierings, and K. Wegener, *An integrated cost-model for selective laser melting (SLM).* Rapid Prototyping Journal, 2013. **19**(3): p. 208-214.

ANNEXES

ANNEX 1

DED machine datasheet

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.

Impeller repaired by LENS 850-R System

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.

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

APPLICATIONS

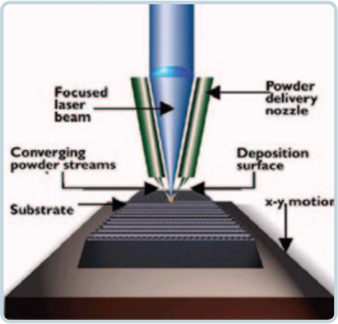
- Repair of worn components
- Rework of mis-machined components
- Modification of tooling for re-use
- Hybrid Manufacturing
- Advanced Product Development

OPTOMEC®
Additive Manufacturing Systems—from NANO to MACRO™

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

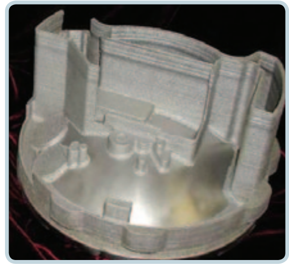
Tel: 505-761-8250
Fax: 505-761-6638
E-mail: requestinfo@optomec.com

Laser Engineered Net Shaping



How the LENS system works:

LENS systems utilizes 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 System

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, 2, 3, or 4 kW IPG Fiber Laser
Software	G-code Workstation Control; STL Editing; Part-Prep slicing
Closed-Loop Controls	Optional melt-pool-sensor
Enclosure Dimensions	3 x 3 x 3 m w/o gas purification system or laser

ABOUT OPTOMEC

Optomec® is the world leading provider of additive manufacturing systems for high-performance applications in the Electronics, Biomedical, Photovoltaic, and Aerospace & Defense markets. These systems utilize Optomec's patented Aerosol Jet Printed Electronics technology and LENS powder-metal fabrication technology.

OPTOMEC®
Additive Manufacturing Systems—from NANO to MACRO™

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

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

ANNEX 2

Matweb datasheet Ti-6Al-4V

Titanium Ti-6Al-4V (Grade 5), Annealed Bar

Categories: Metal; Nonferrous Metal; Titanium Alloy; Alpha/Beta Titanium Alloy

Material Notes: Information provided by Allvac and the references. Annealing Temperature 700-785ºC. Alpha-Beta Alloy

Applications: Blades, discs, rings, airframe, fasteners, components. Vessels, cases, hubs, forgings. Biomedical implants.

Biocompatibility: Excellent, especially when direct contact with tissue or bone is required. Ti-6Al-4V's poor shear strength makes it undesirable for bone screws or plates. It also has poor surface wear properties and tends to seize when in sliding contact with itself and other metals. Surface treatments such as nitriding and oxidizing can improve the surface wear properties.

4 other heat treatments of this alloy are listed in MatWeb.

Key Words: Ti-6-4; UNS R56400; ASTM Grade 5 titanium; Ti6Al4V, biomaterials, biomedical implants, biocompatibility

Vendors: **Click here to view all available suppliers for this material.**

Please click here if you are a supplier and would like information on how to add your listing to this material.

Physical Properties	Metric	English	Comments
Density	4.43 g/cc	0.160 lb/in³	

Mechanical Properties	Metric	English	Comments
Hardness, Brinell	334	334	Estimated from Rockwell C.
Hardness, Knoop	363	363	Estimated from Rockwell C.
Hardness, Rockwell C	36	36	
Hardness, Vickers	349	349	Estimated from Rockwell C.
Tensile Strength, Ultimate	900 MPa	131000 psi	
Tensile Strength, Yield	830 MPa	120000 psi	
Elongation at Break	10 %	10 %	
Reduction of Area	33 %	33 %	
Modulus of Elasticity	114 GPa	16500 ksi	Average of tension and compression
Compressive Yield Strength	860 MPa	125000 psi	
Poissons Ratio	0.33	0.33	
Fatigue Strength	510 MPa @# of Cycles 1.00e+7	74000 psi @# of Cycles 1.00e+7	smooth
Shear Modulus	44.0 GPa	6380 ksi	

Electrical Properties	Metric	English	Comments
Electrical Resistivity	0.000178 ohm-cm	0.000178 ohm-cm	
Magnetic Permeability	1.00005	1.00005	at 1.6 kA/m
Magnetic Susceptibility	0.0000033	0.0000033	cgs/g

Thermal Properties	Metric	English	Comments
CTE, linear	8.60 µm/m-°C @Temperature 20.0 - 100 °C	4.78 µin/in-°F @Temperature 68.0 - 212 °F	
	9.20 µm/m-°C @Temperature 20.0 - 315 °C	5.11 µin/in-°F @Temperature 68.0 - 599 °F	average
	9.70 µm/m-°C @Temperature 20.0 - 650 °C	5.39 µin/in-°F @Temperature 68.0 - 1200 °F	average
Specific Heat Capacity	0.5263 J/g-°C	0.1258 BTU/lb-°F	
Thermal Conductivity	6.70 W/m-K	46.5 BTU-in/hr-ft²-°F	
Melting Point	1604 - 1660 °C	2919 - 3020 °F	

Solidus	1604 °C	2919 °F	
Liquidus	1660 °C	3020 °F	
Beta Transus	980 °C	1800 °F	

Component Elements Properties	Metric	English	Comments
Aluminum, Al	5.5 - 6.75 %	5.5 - 6.75 %	
Carbon, C	<= 0.080 %	<= 0.080 %	
Hydrogen, H	<= 0.015 %	<= 0.015 %	
Iron, Fe	<= 0.40 %	<= 0.40 %	
Nitrogen, N	<= 0.030 %	<= 0.030 %	
Other, each	<= 0.050 %	<= 0.050 %	
Other, total	<= 0.30 %	<= 0.30 %	
Oxygen, O	<= 0.20 %	<= 0.20 %	
Titanium, Ti	87.725 - 91 %	87.725 - 91 %	As Balance; Elemental Composition per ASTM B265
Vanadium, V	3.5 - 4.5 %	3.5 - 4.5 %	

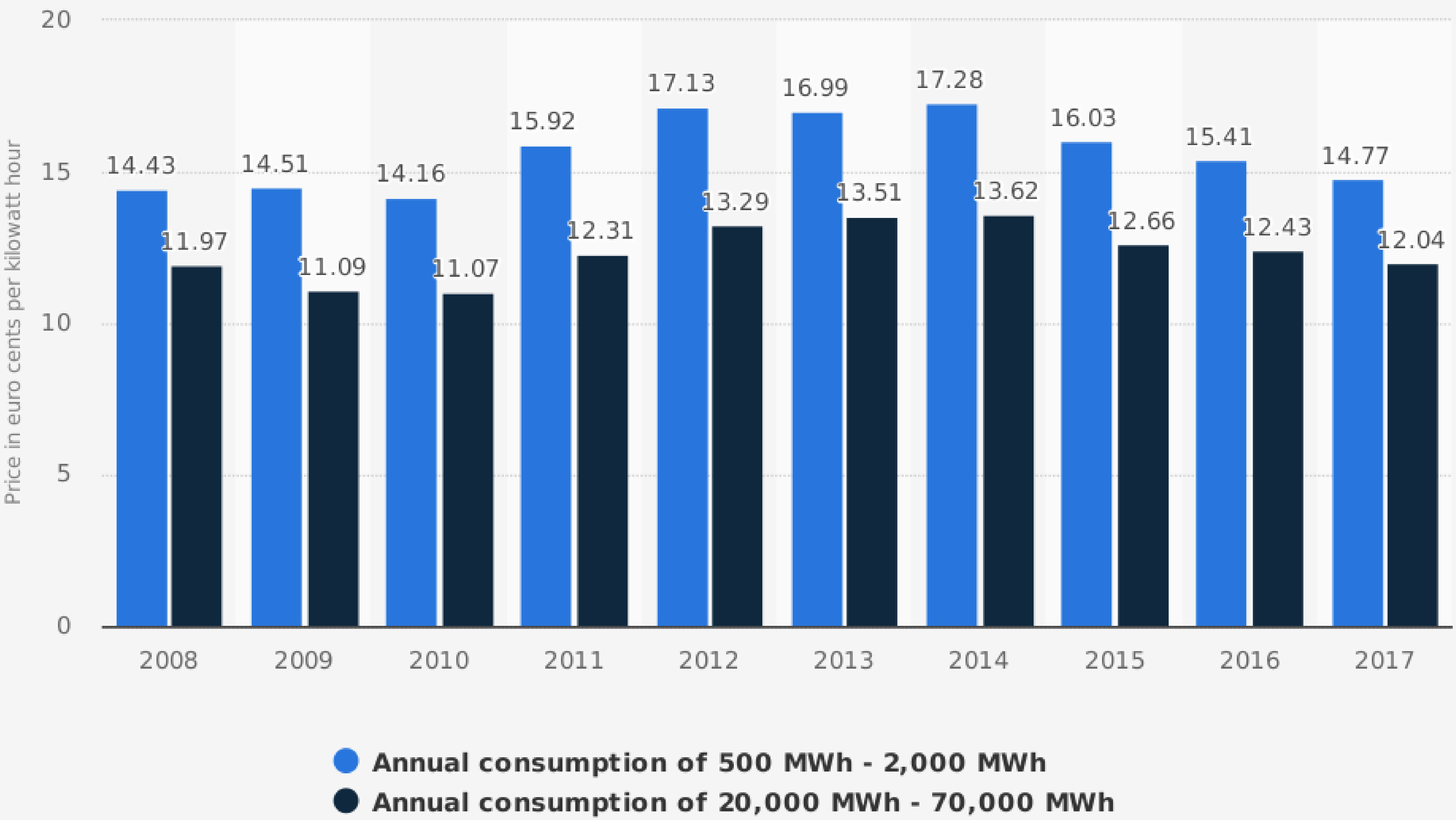
Descriptive Properties			
Velocity of Sound		4.987 km/s	Heat treatment not specified

References for this datasheet.

ANNEX 3

Electricity prices in Europe in 2017

Prices of electricity for industry in Italy from 2008 to 2016 (in euro cents per kilowatt hour)



Source
Eurostat

Additional Information:
Italy; BMWi; 2008 to 2017

ANNEX 4

Quotation price for inert gases

Unità di Rosta
I-10090 Rosta (TO) - Strada Antica di Alpignano, 30
Tel. 011-9567839 - Fax. 011-9567869
www.siad.com - siad@siad.com

SIAD Società Italiana Acetilene Derivati S.p.A.
I-24126 Bergamo - Via S.Bernardino, 92
Capitale Sociale € 25.000.000
N. 00209070168 Reg. delle Imprese Bergamo
R.E.A. Bergamo 15532
Partita IVA e Cod. Fiscale 00209070168

Spettabile : POLITECNICO DI TORINO - Dip. Ing. Gestionale e della Produz.
Corso Duva Degli Abruzzi,24
10129 Torino - TO

Alla c.a. : Ing. Alessandro Salmi

Rosta, 31/10/2017

Oggetto : FORNITURA GAS TECNICI E GRUPPI DI DECOMPRESSIONE PER NUOVO CENTRO IAM
Subject :

Offerta n. 17-08389 del 31/10/2017 DM/dm

Facendo seguito alla Vs. gradita richiesta citata in oggetto, siamo lieti di inviarVi in allegato le nostre migliori condizioni.

Restando a Vs. disposizione per ulteriori chiarimenti, ci è gradita l'occasione per porgerVi i nostri migliori saluti.

Riferimenti del Commerciale : Sig. Daniele Manfrin - +39 (335) 6066120 - daniele_manfrin@siad.eu

Timbro e Firma

Oggetto : **FORNITURA GAS TECNICI E GRUPPI DI DECOMPRESSIONE PER NUOVO CENTRO IAM**
Subject :

Offerta n. 17-08389 del 31/10/2017 DM/dm

INDICE

Gas e Miscele

Descrizione:
Contenitori di Gas e Miscele di differenti volumi
Scopo e destinazione d'uso:
Stoccaggio nelle condizioni di progetto
P massima ammissibile (PS) : 200bar
T minima di progetto : -20°C
Limiti di batteria:
Il sistema è composto da bombole singole o pacchi bombole, di 16 o 25 unità, in pressione e dalle valvole di radice per lo spillamento del gas
Collegamenti con altri sistemi :
Valvola o valvole di radice con connessione gas specifica

Pos.	*Descrizione*	*Quantità n.*	*Unità di Misura*	*Prezzo unitario €*
1	ARGON (Ar) 5.0 - Pacchi 16bbx40l - contenuto: 140,8 m3 di prodotto - pressione: 200 bar - valvola: UNI 11144-8 (ex. 4412)	2	carica	1.056,00
2	ELIO (He) 5.0 - bombola 40l - contenuto: 8 m3 di prodotto - pressione: 200 bar - valvola: UNI 11144-8 (ex. 4412)	2	carica	96,00
3	Trasporto pacco 16 bb	2	Nr.	35,00
4	Oneri Trasporto in Sicurezza pacco	2	Nr.	15,00
5	Trasporto bombola	2	Nr.	4,10
6	Oneri Trasporto in Sicurezza bombola	1	Nr.	2,00
7	MDB annuale N.2 pacchi e N.2 bombole	1	anno	700,00
			Totale €	3.114,20

Servizi, Materiali e Impianti

Descrizione:
Sistema di distribuzione per gas composto da riduttori di pressione e accessori di linea
Scopo e destinazione d'uso: Distribuzione del gas a ciascuna utenza
P esercizio : 10 bar
P mass. ammissibile (PS) : 18 bar
T minima di progetto : -20 °C
Limiti di batteria: Il sistema prevede gli elementi di seguito specificati.

- Gruppi di riduzione di primo stadio
- Punto d'uso di intercettazione del gas in prossimità dell'utenza
- Accessori di sicurezza

Collegamenti con altri sistemi:
Valvola d'intercettazione o valvole di radice con connessione gas specifica

Pos.	*Descrizione*	*Quantità n.*	*Unità di Misura*	*Prezzo unitario €*
1	IMPIANTO DISTRIBUZIONE ARGON			
2	QUADRO SA 400/15 08-10 N2 AR ARIA HE MIXIN	1	Nr.	

Scheda tecnica n.0013 - Codice Prodotto:60001527

CARATTERISTICHE
- Due riduttori di pressione monostadio a membrana con filtro sinterizzato in ingresso
- Corpo e componenti metallici a contatto del gas in ottone, membrana in acciaio inox AISI 302, in buna o viton per i modelli con pressione di uscita 14÷16 e 18÷20 bar
- Manometri di alta e bassa pressione Ø63 in ottone, con scala graduata in bar, conformi alla norma EN 837 classe di precisione 1.6.
- Tre valvole di sfiato sovrapressione.
- Connessione alla serpentina o ai gruppi di estensione differenziata per gruppi di gas compatibili
- Due gruppi di intercettazione AP agli ingressi con valvola spurgo (con raccordo a compressione per tubo Øest. 6 mm).
- Possibilità di spurgo della sola serpentina.
- Due valvole di ritegno con filtro sinterizzato agli ingressi con funzione di valvola a pressione residuale.
- Gruppo di intercettazione in uscita, con raccordo completo di dado e codolo a saldare in acciaio inox AISI 316L per tubo Ø est. 10 mm, con presa per bonifica BP ¼" GF.
- Sistema ad inversione automatica delle fonti di di alimentazione all'esaurimento della fonte collegata.
- Pressione di scambio pretarata: 8÷10 bar per i modelli f.s. 15; 14÷16 e 18÷20 bar per i modelli f.s. 25.
- Pannello di sostegno in alluminio anodizzato.
- Collegamento a due bombole tramite serpentine.
- Possibilità di estensione per il collegamento di più bombole utilizzando GRUPPI C.
- Elastomeri e guarnizioni compatibili con i gas utilizzati secondo Praxair Standard EN-55.
- Trattamento superficiale di nichel-cromatura.
- Lavaggio e condizionamento dei componenti per l'impiego con gas puri.

Pos.	Descrizione	Quantità n.	Unità di Misura	Prezzo unitario €
	- Collaudo 100% funzionale e di tenuta con gas azoto. - Norme di servizio e sicurezza accluse ad ogni dispositivo.			
3	ADATTATORE UNI4406 - 1/4 NPTF CROMATO *Scheda tecnica n.5414 - Codice Prodotto:60948426* CARATTERISTICHE - Raccordo in uscita quadri B/SA - Componenti in OT 58 Ni-Cr - Ingresso UNI - Uscita 1/4" NPTF - Completo di O-Ring e guarnizioni in Viton A	1	Nr.	
4	SERPENTONE FLEX AR 2 m *Scheda tecnica n.1018 - Codice Prodotto:60117061* CARATTERISTICHE  - Serpentoni flessibili di collegamento pacchi o rampe. Disponibili in lunghezza (L) 1.000 mm, 1.500mm o 2.000mm - Tubo interno liscio in PTFE (ø interno 6.5 mm). - Rinforzo in doppia treccia in acciaio inox AISI304 ø 11.5 mm alta resistenza. - Completi di cavetto di sicurezza in acciaio zincato e moschettone. - Punzonatura lotto/anno di costruzione. - Connessioni UNI o DIN standard. - Pressione di esercizio 200 bar. Rapporto fra pressione di scoppio e pressione di esercizio > 4. - I serpentoni sono sottoposti a procedimento di lavaggio e sgrassatura. - Collaudo 100% funzionale e di tenuta con gas azoto. - Norme di servizio e sicurezza accluse ad ogni dispositivo.	2	Nr.	
5	VALVOLA DI SICUREZZA OT 18 bar *Scheda tecnica n.5270 - Codice Prodotto:60118147* CARATTERISTICHE:  - Valvola di sicurezza per gas con sede a tenuta piana - Materiali: corpo in ottone - Scarto in apertura (sovra-pressione): 10 % - Sgrassate per uso con ossigeno - Marcate CE cat. IV dir. 97/23/CE	1	Nr.	
6	POSTO PRESA RD 15 N2 AR ARIA HE CO2 MIXIN *Scheda tecnica n.0026 - Codice Prodotto:60001504*	2	Nr.	

Pos.	Descrizione	Quantità n.	Unità di Misura	Prezzo unitario €

CARATTERISTICHE
- Posto presa con riduttore di pressione monostadio a membrana.
- Corpo e componenti metallici a contatto del gas in ottone, membrana in acciaio inox AISI 302, Viton o NBR per f.s. 25 e 60.
- Volantino di regolazione con dispositivo di arresto di sicurezza per impedire il superamento della pressione nominale massima di uscita.
- Valvola di sfiato sovrapressione.
- Manometro di bassa pressione Ø50 in ottone, con scala graduata in bar, conforme alla norma EN 837 classe di precisione 1.6.
- Valvola di intercettazione e regolazione a spillo in uscita.
- Connessioni di ingresso e di uscita con attacco 1/4" NPTF.
- Filtro sinterizzato all'ingresso del riduttore.
- Elastomeri e guarnizioni compatibili con i gas utilizzati secondo Praxair Standard EN-55.
- Trattamento superficiale di nichel-cromatura.
- Collaudo 100% funzionale e di tenuta con gas azoto.
- Assemblaggio in cassetta in alluminio anodizzato.
- Lavaggio e condizionamento per l'utilizzo con gas puri.
- Norme di servizio e sicurezza accluse ad ogni dispositivo.

7	VALVOLA MB PER PUNTI D'USO PN 20 bar	2	Nr.	

Scheda tecnica n.0061 - Codice Prodotto:60111260

CARATTERISTICHE
- Valvola di intercettazione: Versione per installazione a monte di punti d'uso
- Componenti metallici a contatto del gas in ottone (con trattamento superficiale di nickel-cromatura)
- Membrana in BUNA
- Connessione di ingresso 1/4" NPTF e connessione di uscita 1/4" NPTF (versione per sezionamento linea) o 3/8" GF girevole con raccordo 1/4" NPTM (versione per installazione a monte di punti d'uso)
- Possibilità di installazione a parete mediante apposita piastra di fissaggio (fornita come accessorio su richiesta)
- Collaudo 100% funzionale e di tenuta con gas azoto.
- Norme di servizio e sicurezza accluse ad ogni dispositivo.

8 IMPIANTO DISTRIBUZIONE ELIO

9	QUADRO SA 400/15 08-10 N2 AR ARIA HE MIXIN	1	Nr.	

Scheda tecnica n.0013 - Codice Prodotto:60001527

CARATTERISTICHE
- Due riduttori di pressione monostadio a membrana con filtro sinterizzato in ingresso
- Corpo e componenti metallici a contatto del gas in ottone, membrana in acciaio inox AISI 302, in buna o viton per i modelli con pressione di uscita 14÷16 e 18÷20 bar
- Manometri di alta e bassa pressione Ø63 in ottone, con scala graduata in bar, conformi alla norma EN 837 classe di precisione 1.6.
- Tre valvole di sfiato sovrapressione.

Pos.	Descrizione	Quantità n.	Unità di Misura	Prezzo unitario €

- Connessione alla serpentina o ai gruppi di estensione differenziata per gruppi di gas compatibili
- Due gruppi di intercettazione AP agli ingressi con valvola spurgo (con raccordo a compressione per tubo Øest. 6 mm).
- Possibilità di spurgo della sola serpentina.
- Due valvole di ritegno con filtro sinterizzato agli ingressi con funzione di valvola a pressione residuale.
- Gruppo di intercettazione in uscita, con raccordo completo di dado e codolo a saldare in acciaio inox AISI 316L per tubo Ø est. 10 mm, con presa per bonifica BP ¼" GF.
- Sistema ad inversione automatica delle fonti di di alimentazione all'esaurimento della fonte collegata.
- Pressione di scambio pretarata: 8÷10 bar per i modelli f.s. 15; 14÷16 e 18÷20 bar per i modelli f.s. 25.
- Pannello di sostegno in alluminio anodizzato.
- Collegamento a due bombole tramite serpentine.
- Possibilità di estensione per il collegamento di più bombole utilizzando GRUPPI C.
- Elastomeri e guarnizioni compatibili con i gas utilizzati secondo Praxair Standard EN-55.
- Trattamento superficiale di nichel-cromatura.
- Lavaggio e condizionamento dei componenti per l'impiego con gas puri.
- Collaudo 100% funzionale e di tenuta con gas azoto.
- Norme di servizio e sicurezza accluse ad ogni dispositivo.

Pos.	Descrizione	Quantità n.	Unità di Misura	Prezzo unitario €
10	ADATTATORE UNI4406 - 1/4 NPTF CROMATO	1	Nr.	

Scheda tecnica n.5414 - Codice Prodotto:60948426

CARATTERISTICHE
- Raccordo in uscita quadri B/SA
- Componenti in OT 58 Ni-Cr
- Ingresso UNI - Uscita 1/4" NPTF
- Completo di O-Ring e guarnizioni in Viton A

Pos.	Descrizione	Quantità n.	Unità di Misura	Prezzo unitario €
11	SERPENTINA SD AR HE	2	Nr.	

Scheda tecnica n.0024 - Codice Prodotto:60111317

CARATTERISTICHE
- Serpentina di collegamento bombola completa di maniglia orientabile.
- Tubo in rame Ø 4x7 mm, L = 1000 mm (PTFE DN 6.5 mm per C_2H_2 e C_3H_8).
- Avvolgimento ad anello.
- Trattamento superficiale di nickel-cromatura.
- Codoli e dadi girevoli in ottone
- Guarnizioni compatibili con i gas utilizzati secondo Praxair Standard EN-55.
- Connessione alla bombola secondo standard UNI (Italia) o DIN (Estero), connessione alla rampa secondo gruppi di gas compatibili.
- Lavaggio e condizionamento dei componenti per l'impiego con gas puri.
- Sottoposte a prove di tipo, per la resistenza meccanica a 2.25 volte la pressione massima di esercizio, per la resistenza all'esplosione a 3 volte la pressione di esercizio e a prova delle perdite di carico secondo EN

Pos.	Descrizione	Quantità n.	Unità di Misura	Prezzo unitario €

13221.
- Collaudo 100% funzionale e di tenuta con gas azoto.
- Norme di servizio e sicurezza accluse ad ogni dispositivo.

Pos.	Descrizione	Quantità n.	Unità di Misura	Prezzo unitario €
12	RASTRELLIERA 2 POSTI BOMBOLA	1	Nr.	

Scheda tecnica n.1017 - Codice Prodotto:60116001

CARATTERISTICHE
- La rastrelliere vengono utilizzate per fissare in modo stabile le bombole alla parete nei locali dove vengono impiegate o stoccate, nel rispetto delle norme di sicurezza.
- Una o più selle in materiale plastico antiurto, adattabili ai vari diametri delle bombole, sono montate su di un profilato di sostegno di acciaio zincato che viene fissato a muro con appositi tasselli.
- Le cinghie di materiale sintetico antistrappo consentono il bloccaggio delle bombole.
- La rastrelliera così costituita può essere impiegata per il fissaggio di una o più bombole.
- Componenti: selle di contenimento in materiale plastico ABS, profilato di base in acciaio zincato, cinghie di ancoraggio in fibbia antistrappo.
- E' possibile ordinare le rastrelliere già complete e predisposte per 1,2,3,4, o 5 posti bombola con interasse di 40 cm, oppure di ordinare separatamente la barra profilata (lunghezza 3.5 m), le coppie di semiselle ed i piantoni.

Pos.	Descrizione	Quantità n.	Unità di Misura	Prezzo unitario €
13	VALVOLA DI SICUREZZA OT 18 bar	1	Nr.	

Scheda tecnica n.5270 - Codice Prodotto:60118147

CARATTERISTICHE:
- Valvola di sicurezza per gas con sede a tenuta piana
- Materiali: corpo in ottone
- Scarto in apertura (sovra-pressione): 10 %
- Sgrassate per uso con ossigeno
- Marcate CE cat. IV dir. 97/23/CE

Pos.	Descrizione	Quantità n.	Unità di Misura	Prezzo unitario €
14	POSTO PRESA RD 2.5 N2 AR ARIA HE CO2 MIXIN	2	Nr.	

Scheda tecnica n.0026 - Codice Prodotto:60001497

CARATTERISTICHE
- Posto presa con riduttore di pressione monostadio a membrana.
- Corpo e componenti metallici a contatto del gas in ottone, membrana in acciaio inox AISI 302, Viton o NBR per f.s. 25 e 60.
- Volantino di regolazione con dispositivo di arresto di sicurezza per impedire il superamento della pressione nominale massima di uscita.
- Valvola di sfiato sovrapressione.
- Manometro di bassa pressione Ø50 in ottone, con scala graduata in bar, conforme alla norma EN 837 classe di precisione 1.6.
- Valvola di intercettazione e regolazione a spillo in uscita.
- Connessioni di ingresso e di uscita con attacco 1/4" NPTF.

Pos.	Descrizione	Quantità n.	Unità di Misura	Prezzo unitario €
	- Filtro sinterizzato all'ingresso del riduttore. - Elastomeri e guarnizioni compatibili con i gas utilizzati secondo Praxair Standard EN-55. - Trattamento superficiale di nichel-cromatura. - Collaudo 100% funzionale e di tenuta con gas azoto. - Assemblaggio in cassetta in alluminio anodizzato. - Lavaggio e condizionamento per l'utilizzo con gas puri. - Norme di servizio e sicurezza accluse ad ogni dispositivo.			
15	VALVOLA MB PER PUNTI D'USO PN 20 bar *Scheda tecnica n.0061 - Codice Prodotto:60111260* CARATTERISTICHE - Valvola di intercettazione: Versione per installazione a monte di punti d'uso - Componenti metallici a contatto del gas in ottone (con trattamento superficiale di nickel-cromatura) - Membrana in BUNA - Connessione di ingresso 1/4" NPTF e connessione di uscita 1/4" NPTF (versione per sezionamento linea) o 3/8" GF girevole con raccordo 1/4" NPTM (versione per installazione a monte di punti d'uso) - Possibilità di installazione a parete mediante apposita piastra di fissaggio (fornita come accessorio su richiesta) - Collaudo 100% funzionale e di tenuta con gas azoto. - Norme di servizio e sicurezza accluse ad ogni dispositivo.	2	Nr.	
	RACCORDERIA			
16	RACCORDO A COMPRESSIONE IX 1/4" NPTM - 12mm *Scheda tecnica n.5401 - Codice Prodotto:60122322* CARATTERISTICHE - Raccordo con doppia ogiva a tenuta metallica	10	Nr.	
17	RACCORDO A T 1/4"NPTF NICHELATO *Scheda tecnica n.5414 - Codice Prodotto:60125679*	2	Nr.	
18	RACCORDO 1/4 NPTM-1/2 GFG *Scheda tecnica n.5414 - Codice Prodotto:60125680*	2	Nr.	
	MANO D'OPERA PROGETTO E MANO D'OPERA			
19	Installazione materiale a corpo - Installazione quadri di decompressione e apparecchiature - Prove di tenuta e di collaudo - Conforme alle norme italiane ed europee di riferimento e secondo proc. ACR 1141 - Materiali di consumo inclusi (collari, staffe, viti, cercafughe, etc..)	1	Nr.	

Pos.	*Descrizione*	*Quantità n.*	*Unità di Misura*	*Prezzo unitario €*

Totale € 7.100,00

Documentazione a corredo della fornitura

- √ Verbale di esecuzione a regola d'arte e Verbale di collaudo
- √ Verbale di collaudo
- √ Verbale di consegna dell'impianto
- √ Schemi elettrici, funzionali e fluidici dei componenti
- √ Manuale d'uso e manutenzione
- √ Schede di sicurezza dei Gas e schede di prodotto

Si intendono inclusi nella fornitura

- √ Installatori specializzati
- √ Dotazione antinfortunistica per i nostri tecnici ed installatori
- √ Posa in opera di apparecchiature e tubazioni se preventivato
- √ Attrezzature per l'esecuzione a regola d'arte
- √ Mezzi di sollevamento per altezze massime di 2 metri
- √ Informazioni pratiche al personale da voi designato
- √ Staffaggio di strumentazione e tubazioni (materiale incluso)
- √ Verifica all'installazione in base alle norme vigenti
- √ Bonifica: eliminazione di aria atmosferica ed impurezze particolari dall'impianto
- √ Tenuta: eliminazione del fenomeno di retrodiffusio
- √ Conformità: verifica e controllo delle pressioni e portate di gas all'utilizzo
- √ Funzionalità: Verifica tecnica del funzionamento di ogni apparecchiatura
- √ Etichettatura per tubazioni e gruppi di decompressione

L'offerta non include

- √ Permessi di lavoro
- √ Energia elettrica per le attrezzature dei nostri operatori
- √ Istruzioni al ns. personale sui comportamenti interni da osservare
- √ Mezzi di sollevamento per altezze superiori a 2 metri
- √ Aree di Cantiere
- √ Opere murarie, ripristino di intonaci, scavi di cunicoli
- √ Strutture metalliche e non, per il sostegno delle apparecchiature se non in offerta
- √ Strutture elettriche ed allacciamento a strumenti elettrici se non in offerta
- √ Messa a terra dell'impianto e relativi pozzetti dispersori
- √ Verniciatura tubazioni e/o pareti
- √ Gru e altri mezzi di sollevamento qualora necessari
- √ Raccordi speciali per collegamento a vostri strumenti
- √ Gas Azoto per le attività complementari la ns. fornitura
- √ Le conservazioni di materiali e apparecchiature non installate
- √ Segnaletica generica di sicurezza
- √ Classificazione e aggiornamento delle aree classificate (Dir. 99/92/CE Atex)

Condizioni di Vendita

Tempo di Consegna	: Gas puri in bombole e pacchi : 2 giorni da ricevimento vostro ordine Materiali : 15 giorni da ricevimento ordine
Mezzo di Spedizione	: A mezzo ns. corriere con addebito degli oneri di consegna.
Imballo	: Recipienti SIAD a rendere - addebito per messa a disposizione bombole (mdb).
Pagamento	: 30 giorni
Metodo di pagamento	: Data fattura rimessa diretta
IVA	: esclusa
Validità	: 30 Giorni
Note	: **CLAUSOLE DI CONFIDENZIALITA'** Il contenuto di questa offerta è assolutamente riservato e non può essere divulgato e/o comunicato, in tutto o in parte, a terzi e non può essere utilizzato per fini diversi da quello di valutare la presente offerta e della possibile trattativa con SIAD. Il presente impegno di riservatezza e non uso sopravviverà per 5 anni alla scadenza della presente offerta. **N.B.** Le immagini e le foto inserite sono a carattere puramente indicativo e potrebbero non rappresentare esattamente il prodotto descritto.
Note aggiuntive	: Si precisa che i corrispettivi indicati nella presente offerta saranno maggiorati dei costi che Siad dovesse sostenere per adempiere a specifiche previsioni (ad esempio, apertura di conti correnti dedicati etc.) del Codice degli Appalti e/o del Sistema Monitoraggio finanziario delle Grandi Opere (MGO) e/o di analoghi provvedimenti. Pertanto, nel caso in cui la fornitura di cui alla presente offerta fosse destinata ad appalti/forniture pubblici, si consiglia al cliente di segnalarlo immediatamente a Siad, fornendo i dettagli del caso, e di chiedere un aggiornamento della presente offerta, che tenga conto dei suddetti ulteriori costi.

Condizioni di Vendita Impianti

Inizio Lavori	: 15 giorni da ricevimento Ordine
Garanzia	: 12 mesi dalla data del verbale di consegna dell'impianto e comunque limitatamente alla riparazione ed all'eventuale sostituzione dei particolari che dovessero risultare affetti da vizi o difetti di costruzione.
Collaudo	: Sarà effettuato a ns. cura alla presenza di Vs. personale espressamente delegato allo scopo mediante prova di tenuta e funzionalità con Azoto.
Collegamenti Elettrici	: a Vs. Carico. Si ricorda che la presenza di gas infiammabili potrebbe modificare la vostra classificazione dell'area.
Responsabilità	: SIAD S.p.A. non si assume alcuna responsabilità sulla rispondenza dei vostri locali in cui verranno installati i dispositivi di decompressione e le relative bombole, in merito alle norme attuali sulla Prevenzione Incendi e relative autorizzazione.
Note sull' Impianto	: Se già non facesse parte di codesta offerta, si consiglia l'installazione di sistema di rilevazione Fughe Gas. Parte del lavoro potrebbe essere affidato da Siad in subappalto. Costi specifici per la sicurezza pari a € 213.

Timbro e Firma

ANNEX 5

Cost model Excel spreadsheet (1 kg)

Cost element	Value	Process step
Material	€ 299.00	Build
Machine Preparation	€ 166.26	Machine Preparation
Electrical Energy	€ 70.08	Build
Machine	€ 64.40	Build
Thermal Treatment	€ 35.00	Thermal Treatment
Quality Control	€ 32.50	Quality Control
CAD Preparation	€ 27.50	CAD Preparation
Gas	€ 6.28	Build
Labor	€ 2.50	Build
Small Maintenance	€ 0.55	Build
Total Cost	€ 704.07	

Variables	Value	Unit
Mass	**1.00**	**kg**
Machine Deposition Rate	**0.50**	**kg/h**
Build Time	**2.00**	**h**

Specific cost estimate	3119.04	€/dm^3
	3.12	€/cm^3

Total Cost | Machine Preparation | Material | Machine | Electrical Energy | Small Maintenance | Labor | Gas | Thermal Treatment | Quality Control

Item	Value	Unit
Labor cost (C_{labor})	25	€
Overheads cost (C_o)	30.00	€
CAD Preparation time (t_{cp})	0.50	h
CAD Preparation cost (C_{cp})	**27.5**	€

$$C_{cp} = t_{cp} \times (C_{labor} + C_o)$$

Total Cost | CAD Preparation | Machine Preparation | Material | Machine | Electrical Energy | Small Maintenance | Labor | Gas | Thermal Treatment | ...

Item	Value	Unit
Labor cost (C_{labor})	25.00	€
Machine cost (C_{mach})	32.20	€
Holding time ($t_{holding}$)	0.25	h
Powder preparation time	0.25	h
Laser calibration time (t_{lc})	0.25	h
Inert gas preparation time (t_{gp})	0.49	h
Set-up time (t_{set-up})	1.24	h
Gas flow	2.50	m^3/h
Chamber volume	1.22	m^3
Gas price	7.50	€/m^3
Washing times	5.00	
Platform cost ($C_{platform}$)	50.00	€
Number of parts to produce (N)	1.00	
Machine Preparation cost (C_{mp})	**166.262**	€

$$C_{holding} = t_{holding} \times (C_{labor} + C_{mach})$$

$$C_{pp} = t_{pp} \times (C_{labor} + C_{mach})$$

$$C_{lc} = t_{lc} \times (C_{labor} + C_{mach})$$

$$C_{gp} = t_{gp} \times (C_{labor} + C_{mach})$$

$$C_{mp} = t_{set-up} \times (C_{labor} + C_{mach}) + \frac{C_{platform}}{N}$$

Total Cost | Machine Preparation | Material | Machine | Electrical Energy | Small Maintenance | Labor | Gas | Thermal Treatment | Quality Control

Item	Value	Unit
Mass	1.00	kg
Material price	230.00	€/kg
Powder wasted percentage	30.00	%
Material cost	**299**	€

Item	Value	Unit
Build time (t_b)	2.00	h
Machine price	700000.00	€
Machine overall utilization	25000.00	h
Production overhead percentage	15.00	%
Total machine hourly rate	32.20	€/h
Machine cost	**64.40**	€

$$machine\ hourly\ rate = \frac{price}{utilization} = \frac{700\ 000\ €}{25\ 000\ h} = 28\ €/h$$

$$total\ machine\ hourly\ rate = 28\ \times (1 + 0.15) = 32.2\ €/h$$

Item	Value	Unit
Electrical energy price	0.12	€/kWh
Mass	1.00	kg
Energy consumption rate (ECR)	584.00	kWh/kg
Electrical energy consumption	584.00	kWh
Electrical Energy cost	**70.08**	€

$$electrical\ energy\ cost = consumption \times price$$

$$ECR = \frac{electrical\ energy\ consumed}{mass\ deposited}$$

$$electrical\ energy\ consumed = ECR \times mass\ deposited$$

Item	Value	Unit
Small maintenance time (t_{sm})	1.00	h
Build time (t_b)	2.00	h
Labor cost (C_{labor})	25.00	€/h
Time Between Small Maintenance (TBSM)	200.00	h
Replacement parts cost (C_{rp})	30.00	€
Small Maintenance Cost ($C_{sm,job}$)	**0.55**	€

$$C_{sm} = t_{sm} \times C_{labor} + C_{rp}$$

$$C_{sm,job} = C_{sm} \times \frac{t_b}{TBSM}$$

Item	Value	Unit
Build time (t_b)	2.00	h
Labor cost (C_{labor})	25.00	€/h
Percentage (p)	5.00	%
Labor cost per job	**2.50**	€

$$C_{labor,job} = C_{labor} \times t_b \times p$$

Item	Value	Unit
Build time	2.00	h
Mass	1.00	
Gas price	7.50	€/m³
Volume gas consumed	0.40	m³/h
Gas consumption	0.80	m³
Hourly maintenance cost	0.14	€/h
Maintenance	0.28	€
Gas cost	**6.28**	€

$$gas\ consumption = build\ time \times volume\ gas\ consumed$$

$$maintenance = build\ time \times hourly\ maintenance\ cost$$

$$gas\ cost = consumption \times price + maintenance$$

Item	Value	Unit
Thermal Treatment cost	35.00	€
Number of parts in the thermal treatment (N)	1.00	
Thermal Treatment cost per part	**35**	€

$$C_{tt,part} = \frac{C_{tt}}{N}$$

Item	Value	Unit
CMM device cost (C_{CMM})	45.00	€/h
Labor cost to operate the CMM device ($C_{labor\ CMM}$)	20.00	€/h
CMM operation time (t_{CMM})	0.50	h
Quality Control cost	**32.5**	€

$$C_{qc} = (C_{CMM} + C_{labor\ CMM}) \times t_{CMM}$$

ANNEX 6

Cost model Excel spreadsheet (0.178 kg)

Cost element	Value	Process step
Material	€ 53.22	Build
Machine Preparation	€ 166.26	Machine Preparation
Electrical Energy	€ 12.47	Build
Machine	€ 11.46	Build
Thermal Treatment	€ 35.00	Thermal Treatment
Quality Control	€ 32.50	Quality Control
CAD Preparation	€ 27.50	CAD Preparation
Gas	€ 1.12	Build
Labor	€ 0.45	Build
Small Maintenance	€ 0.10	Build
Total Cost	€ 340.08	

Variables	Value	Unit
Mass	**0.178**	**kg**
Machine Deposition Rate	**0.50**	**kg/h**
Build Time	**0.36**	**h**

Specific cost estimate	8463.84	€/dm^3
	8.46	€/cm^3

Total Cost | Graphs | Graphs kg Comparison | Graphs 10% | Graph Pareto | CAD Preparation | Machine Preparation | Material | Machine | Electrical Ene ...