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ALTA SCUOLA POLITECNICA
POLITECNICO DI MILANO | POLITECNICO DI TORINO

LAMP

- LASER ADDITIVE MANUFACTURING & PROTOTYPING -

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Summary

"Mechanical performance optimization through specific product design is still mostly constrained by the limits of current manufacturing technologies, which are often unfit to combine product complexity with cost and resource efficiency" (Borealis Project, 2014). This trade-off, together with the one between cost and customizability, can be overcome only by adopting a revolutionary approach to manufacturing. Additive Manufacturing (AM), in distinction from traditional processes such as casting and machining, is a promising emerging technology that is proving capable of producing parts in different materials, from plastic to metal, whose cost per piece is independent from the complexity and the number of produced parts.

AM is getting more and more attention in the recent years. As a matter of facts, its market, consisting of all products, materials and services, was worth around 3.07 billion USD in 2013 and is expected to show a double-digit growth in the next decades. AM revenues have grown steadily during the last 25 years, with an average Compound Annual Growth Rate (CAGR) equal to 27%. Furthermore, this pace has considerably increased during 2011/2013, pushing the growth up to 32.3% (Wohlers Report, 2013). There is also a strong commitment by the public sector to push forward the development of AM. This is proven by the huge funding the European Union, through the so called *Horizon 2020* program, is providing to foster research into this emerging technology.

In this context, more and more enterprises are seeking for entering this market for basically two reasons. First of all, AM is a potentially profitable field. Secondly, as it is a disruptive innovation with the capacity to revolutionize the way in which products are manufactured, embracing AM is crucial for staying in the market. However, the highly competitive environment, together with the existing problems related to intellectual properties and issues concerning the technology readiness level, make it difficult for new actors to enter the market.

In this framework, the present ASP Multidisciplinary Project aims to provide guidelines to its industrial partner *Prima Industrie*, which is planning to enter the metal AM market in the next few years. This objective has been accomplished by pointing out the requirements of the manufacturing industry, developing an in-depth analysis of the State of the Art (SoA) and the market outlook of metal AM and, finally, understanding the advantages and the critical aspects of the design process of mechanical components to be manufactured using AM. As the core technology *Prima Industrie* has developed is the laser for industrial applications, the focus of this report is on metal laser AM, although this latter is often compared to its alternative, the electron beam technology, in order to point out its strengths and weaknesses.

The SoA of metal AM has been depicted through a close interaction of all the team members, whose backgrounds are strongly different. The team first documented broadly on the AM topic, so that a common lexicon was built, then each team member went deep in analyzing the field that best matched his/her competencies. Finally, all the individual research was shared among the rest of the group.

The requirement analysis, instead, has been carried out through a substantial bibliographic research, complemented by interviews to technology experts and industrial players, whose case studies are presented. This way, it has been possible to point out the technical, corporate and policy requirements, along with the trade-offs and the limits of current technologies.

The objectives of the last phase of the project have been twofold: theoretical and practical. On one hand, the team investigated the possible ways in which AM machines may develop, in an effort of shaping the "machine of the future" both in terms of what is demanded by the market and what may be technologically feasible. Moreover, future market trends were investigated. On the other hand, the practical part was devoted to the development of two technological demonstrators, which allow to have a deeper insight into the AM technologies from a designer's point of view.

The first demonstrator selected by the team is a structural component for aerospace application: the original part has been redesigned, optimizing it from the structural and topological point of view and conceiving it for the AM production; such activity has been carried out with the help of structural analysis and shape optimization software.

The second demonstrator belongs to the biomedical field and is capable of effectively pointing out the potentialities of AM technologies in terms of geometries impossible to be obtained with traditional manufacturing techniques.

Part I

Introduction

Chapter 1

The Laser Additive Manufacturing and Prototyping (LAMP) project

In this chapter, after a brief introduction to the topic, a description of the problem addressed by the project is presented. The requirements of the external institution that supported the project are pointed out, along with a detailed overview of the methodology adopted by the LAMP team.

1.1 Introduction

"The industrial revolution of the late 18^{th} century made possible the mass production of goods, thereby creating economies of scale which changed the economy, and society, in ways that nobody could have imagined at the time. Now a new manufacturing technology has emerged which does the opposite." Additive Manufacturing (AM), also known as 3D-Printing, "makes it as cheap to create single items as it is to produce thousands and thus undermines economies of scale. It may have as profound an impact on the world as the coming of the factory did" [1].

The underlying idea of AM is that a part can be manufactured simply adding layers of raw material one on top of the other. The different layers are bound together thanks to an energy source that partially melts the printing medium. This approach allows to fabricate parts directly starting form their 3D Computer-Aided Design (CAD) models, without the need for process planning. Each layer has a finite thickness, therefore the resulting part will be an approximation of the 3D model, as clearly shown in Fig. 1.1. As the manufacturing process is independent from the shape of the product, the concept of economies of scale does not apply to AM. Furthermore, the layerwise approach makes possible the production of complex shapes without the need of additional fixtures or a detailed analysis of the part geometry to determine, for instance, the order in which different features can be fabricated.

AM technology was originally developed to print using polymeric materials. However, the recent breakthroughs in the field of high power laser sources are opening the possibility of employing metal powders as printing medium, thus dramatically extending the field of applicability of this technology.

Figure 1.1: CAD image of a teacup with further images showing the effects of building using different layer thicknesses [2].

1.2 Description of the problem

The "Laser Additive Manufacturing and Prototyping" ASP multidisciplinary project has been developed in close collaboration with *Prima Power*, a division of *Prima Industrie* (TO, Italy), a multinational company, leader in the production and commercialization of laser machinery for industrial applications, with more than 12,000 installed machines, willing to explore the possibilities offered by AM technologies. The company employs 1,500 people and has production facilities across four countries (Italy, USA, China, and Finland), with a worldwide commercial and after-sale presence. Nowadays it produces industrial machinery for bending, shearing, punching, laser machines and systems for 2D and 3D cutting, welding and drilling, along with a wide range of software solutions supporting the production process. Thanks to their 35-years long experience in the fields of laser production and machine control, *Prima Industrie* has developed the necessary know-how that would enable their entrance in the laser AM sector.

At the present state, AM systems market is rather small if compared to the wider machine tool market, as the former accounts for 1.3% of the latter [3]. However, AM is getting more and more attention in the recent years. As a matter of facts, its market, consisting of all products, materials and services, was worth around 3.07 billion USD in 2013 and is expected to show a double-digit growth in the next decades. AM revenues have grown steadily during the last 25 years, with an average Compound Annual Growth Rate (CAGR) equal to 27%. Furthermore, this pace has considerably increased during 2011/2013, pushing the growth up to 32.3% [4]. Moreover, the market is expected to quadruple during the 2012-22 timeframe [3].

There is also a strong commitment by the public sector to push forward the development of AM. This is proven by the huge funding the European Union, through the so called *Horizon 2020* program, with 80 billion Euros available in the 2014-20 period provided to foster research into this emerging technology.

In this context, more and more enterprises are seeking for entering this market for two reasons. First of all, AM is a potentially profitable field. Secondly, as it is a disruptive innovation with the capacity to revolutionize the way in which products are manufactured, embracing AM is crucial for staying in the market. As a consequence, the LAMP team was supposed to provide a comprehensive picture of the present situation and future trends regarding the AM field, in order to assist its external partner in taking the right decisions. In fact, the highly competitive environment, together with the existing problems related to intellectual properties and issues concerning the technology readiness level, make it difficult for new actors to enter the market.

AM systems already on the market have been conceived in a research environment and lack of the productivity and process optimization of mature machine tools; therefore, they are more likely to be used for prototyping, rather than full scale functional parts. In this context, *Prima Industrie* sees the possibility to make a blue ocean strategic move, creating a machine with high productivity and innovative features, more suitable for industrial applications. Therefore, the team's external partner wants to fully exploit its present know-how in laser sources and industrial machinery for the design and implementation of the next generation laser AM machine.

Given the requirements of *Prima Industrie*, the LAMP team was asked to identify and report the present state and future trends of the AM sector providing a technical insight of the State of the Art (SoA) for the technology and to highlight the key features that the next AM machine should have. To explore the potential and actual limitations of the technology, providing an in-depth requirement analysis also from the end user point of view, the ASP team focused its efforts in re-designing and optimizing a real component presently manufactured by using a traditional subtractive approach.

1.3 Methodology

As may emerge from the activity timeline summarized in Tab. 1.1, the LAMP project was carried out in two phases. At the beginning, the team members worked in parallel, documenting broadly on the metal AM topic, in order to develop a common background. In fact, as the technology is still in its early stages with respect to industrial application, no one was specifically trained to deal with it. After the very first documenting phase, every team member analyzed in depth his field of competence. Indeed, the multidisciplinary composition of the team enabled a complete analysis of the process. Laser sources were investigated by the electronical engineer, metal powders and microstructures by the material engineer, machines by the mechanical engineer, applications by the biomedical engineer, costs by the management engineer, software and design for AM by the designers. The output of this first phase was the redaction of a technical report dealing with AM technologies, materials, machines, applications, software, and cost analysis.

This technical report, representing a comprehensive picture of the SoA of AM technology, was submitted to the tutors in November 2014, who approved it the following month. Further integrations were subsequently added to it, dealing with the mechanical properties of produced parts and the history of AM with its core patents.

The objectives of the second phase of the project were twofold: theoretical and practical. As far as the theoretical part is concerned, the team focused its attention on investigating future market trends enabled by new technologies, and in particular by metal AM. In this framework, the technology readiness level was assessed to understand when, and if, it will be capable to complement and/or replace traditional manufacturing techniques. Starting from *Q1 2015*, the team tried to understand how Italian companies already involved in metal AM are using it. To this purpose, the *Avio Aero* production plant

		Q2-2014 (APR-MAY-JUN)	Q3-2014 (JUL-AUG-SEP)	Q4-2014 (OCT-NOV-DEC)	Q1-2015 (JAN-FEB-MAR)	Q2-2015 (APR-MAY-JUN)	Q3-2015 (JUL-AUG-SEP)	Q4-2015 (OCT-NOV-DEC)
REQUIREMENTS ELICITATION &STATE OF THE ART ANALYSIS & SCENARIO	Visits, interviews	Visit to PPP Lab and IIT Lab in Torino		Visit to Prima Industrie in Torino	Visit to Avio Prop in Cameri (NO)	Visit to Sinteaplustek in Assago (MI) & Interview to Medacta		
	Research activities	Understanding of the technology	Technical report redaction	Report review	Future trends and scenario analysis	Updating of the report with integrations and revised parts		
	Conferences	MakeForum attendance at POLIMI		Rapid Manufacturing Forum attendance at Malpensa Airport				Conference on AM attendance at EMO Milano 2015
TOPOLOGICAL OPTIMIZATION & DEMONSTRATOR PRINTING				Selection of the case study	CAD development, topological optimization of the part and validation analyses (iterative process)		Cost analysis of the optimized part	3D printing of the final metal demonstrator and machining of the traditional component
FINAL ASP REPORT & POSTER					Mid-term review presentation	Organization of the previously produced material according to the ASP index		Handing in of the report and poster

Table 1.1: Timeline of the set of activities carried out by the LAMP team.

in Cameri (NO, Italy) and *Sinteaplustek* headquarter in Assago (MI, Italy) were visited, while *Medacta* (Switzerland) was interviewed. The information gathered during such visits helped the team to complete the requirement elicitation process. Once the SoA was clearly depicted, the team proceeded with the trade-off analysis of technical requirements of AM, in order to understand its present limits and how they will evolve in the near future. This process led the team to depict the winning features that the next generation AM machine need to exhibit in order to widely replace traditional manufacturing processes, establishing itself as a radical innovation, and not just a technology suitable for niche applications.

The practical part was focused on the re-designing and printing of a real component, in order to understand the design possibilities and processing issues of AM technology. The selection of the specific case study was influenced by the availability of product specifications and by considerations about the relevance of AM in its production. Therefore, a metal structural part for the aerospace field was chosen as demonstrator. The existing component, best suited for traditional subtractive machining, was re-designed through structural and topological optimization, conceiving it for the AM production. Such process was carried out using specific software, like *SolidThinking Inspire* by *Altair Engineering*. To understand the impact of redesigning for AM, an analysis of the cost savings over the component life-cycle was carried out. The optimized component was printed at *Istituto Italiano di Tecnologia* (IIT) of Turin. Moreover, the original geometry was machined with subtractive techniques, in order to better appreciate the final results. Furthermore, the team investigated different fields of application and selected an additional demonstrator, capable of effectively pointing out the potentialities of the AM technologies in terms of shapes impossible to be obtained with traditional manufacturing technologies.

Part II

Users' requirement analysis

Chapter 2

Stakeholders

In this chapter, the stakeholders involved in metal AM are presented, and their characteristics and peculiarities are outlined. As Tab. 2.1 shows, this revolutionary technology is capable of having a transversal influence, affecting very different sectors on different scales. It is also pointed out that public institutions can have an extremely important role in fostering the widespread of metal AM, not only by funding research at an academic level, but also by subsidizing the industrial sector.

2.1 End users

Metal AM has flourished considerably in the last few years especially in certain sectors. In particular, it is possible to distinguish two markets in which it is becoming fundamental in product development: one is the industrial market (which includes biomedical, aerospace and automotive sectors), the other one is the consumer market (which includes, for instance, the fashion industry).

All the aforementioned sectors require:

- design freedom for complex geometries;
- simplified assembly process;
- short lead times;
- introduction at sustainable cost difficult to cut and to cast materials, even in mass production.

Biomedical sector The biomedical industry has established itself as a relevant user of AM and has been the third largest sector using it over the past ten years [5]. Since September 2010, the *American Food and Drug Administration* (FDA) has approved several metal AM implant, opening new perspectives for this emerging technology. Its range of applications spans from the creation of surgical devices to prosthetic implants and hearing aids.

This sector requires the manufacturing of complex parts to be created specifically for the patient at reasonable costs and employing material that are biocompatible, robust and light such as Titanium.

The crucial challenge in orthopaedics is that nothing is as individual as the human body and the implant should adapt perfectly to the body, be quickly accepted and, also, enhance the patient‘s life. AM enables to produce lattice structures and porous surfaces that accelerate the healing process considerably.

STAKEHOLDERS

1 END USERS	2 DIRECT COMPETITORS	3 INDIRECT COMPETITORS
Biomedical sector Aerospace sector Automotive sector Other sectors AM service providers	EOS Renishaw Trumpf SLM Technologies Arcam 3D Systems OptoMec POM Group	Companies in the metal supply chain
4 SUPPLIERS	**5 PUBLIC INSTITUTIONS**	**6 STANDARD-SETTING BODIES**
Metal powder suppliers Printing software suppliers Component suppliers	European Union Italian Government Universities PPP Lab IIT Trade unions Local communities	ISO TC261 ASTM F42

Table 2.1: Stakeholders involved in the metal AM sector.

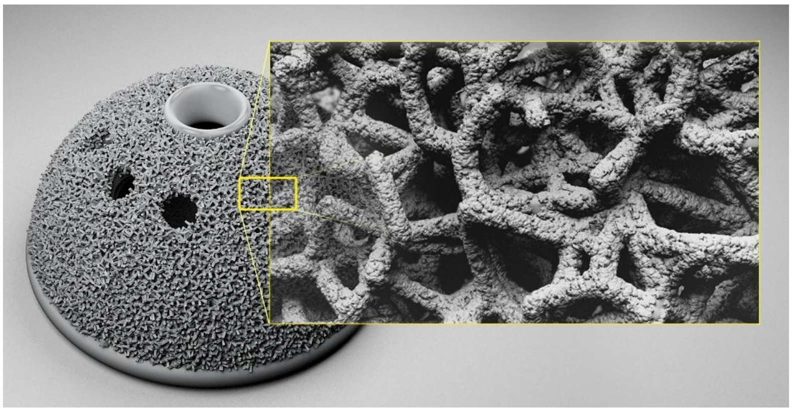


Figure 2.1: Hip implant with lattice structure for improved osseointegration [6].

Osseointegration (the firm connection between bone and medical implant without formation of a fibrous capsule) is, in fact, promoted by the generation of a rough surface area on the prosthesis, as depicted in Fig. 2.1. This is one of the most notable advantages introduced by AM in the biomedical field.

Another interesting advantage introduced by AM in the medical industry is that, by using DED technologies, it is possible to produce multi-material and functionally-graded orthopaedic implant components. These constructs are made of different materials with optimized transitional areas. In this way, the bulk and the surface of the prosthesis have different mechanical and fatigue properties, the implant can be protected from corrosion and the transition from one component to the adjacent one is optimized [7].

Furthermore, complex parts (either prostheses, orthotics or exoskeletons) can be created specifically for a single patient using 3D data obtained from a medical imaging study like, for instance, computed tomography or magnetic resonance and producing a 3D model of the patient's internal skeleton. Customized implants enable the optimization of the healing treatment, the minimizing of hospital stays and side effects.

In recent years, the dental industry is experiencing a rapid growth, mainly due to an increasing interest in having aesthetic teeth. This is one of the reasons that accounts for the explosive growth of AM within the dental industry, that is still the fastest growing field of application for additive techniques [5]. In particular, these unconventional technologies are apt to produce any kind of dental products, and metal AM is already applied in order to make bridges, crowns, removable partial dentures, and implants.

Aerospace sector The aerospace industry is one of the first sectors using metal 3D-printing. While at the beginning AM was only used to produce prototypes, now it is expected with further research and development that the technology will be increasingly used for production of functional parts [8]. The users' key drivers are:

- reducing the buy-to-fly ratio of metallic components, i.e. the weight ratio between the raw material used for a component and the weight of the component itself;
- weight reduction, also through new or optimized design;
- high quality and reproducibility of components.

Moreover, the ability of AM to enable advanced repair operations through the selective re-application of materials has far reaching economic implications. In fact, AM makes it possible to reshape parts, to correct machining and design errors and, in addition, to repair intricate surfaces and volumes damaged by use or corrosion or so on.

This application gives an attractive return on investments without sacrificing the quality. Many aerospace companies in which damaged parts were considered difficult or even impossible to repair up to a few years ago as they required too expensive part replacements, are now embracing laser AM to repair their worn or damaged products.

Automotive sector Automotive is at the moment a strong sector for AM; actually, it is the second largest sector. More and more car manufacturers currently benefit from AM mainly in the production of concept cars as metal AM is increasingly used to produce prototypes of different components and therefore to improve the product development process. Consequently, concept cars are built faster than with traditional methods.

The requirements of AM specific for the automotive sector are:

- very high manufacturing flexibility with high variability of production mix and production volumes;
- design freedom to obtain rapid and cheap prototyping of experimental solutions and therefore reduce the time-to-market;
- possible use in reparation of components.

Both the racing sector and the vehicles serial production one constitute important fields for the application of AM technology. In particular, almost all the areas of an automobile could be redesigned in a completely new way taking advantage of all the benefits introduced by this new technology. Moreover, in the motor racing field, innovative ideas and technologies are easily experimented in order to understand whether and how to introduce them in serial production of vehicles thanks to the rapid prototyping approach [6].

Other sectors AM is not subjected to design restrictions and gives maximum freedom of creation. It opens up a huge range of new possibilities for designers who can give vent to their creativity. In fact, AM makes it possible to turn any thinkable model into a real product economically, flexibly, quickly, and with minimum use of material.

Some companies have started to use metal AM to produce furniture, home, and office accessories such as tables, chairs, and lamps as well as fashion articles like jewelry, particularly customized and limited editions products, such as jewelry in Gold alloys or 18 karat Gold [6] (an example of which is shown in Fig. 2.2). Other fascinating applications are the production of trophies or sculptures.

Another sector that is taking advantage of the benefits introduced by metal 3D-printing is the sport one. Athlete's equipment is designed to enhance performance, prevent their injury, and increase comfort and enjoyment. Each sportsman has different skills and different requirements, so customization is crucial in this sector and AM makes it possible to reach the desired individualization. At present, metal AM in this field is mainly used for prototyping in order to carry out form and fit tests.

A further challenge that sport industry has to face is the need for lighter and lighter equipment so that athletes improve their performances. A case in point is the first 3D-printed metal frame represented in Fig. 2.3, which is the result of a collaboration between *Empire Cycles*, a British bike company, and *Renishaw*.

Figure 2.2: Additively manufactured Gold necklace [6].

Figure 2.3: First 3D-printed bike frame [9].

AM service providers Service providers are typically relatively small companies that purchase AM machines, integrate the technology with conventional part manufacturing and finishing techniques, and sell end parts. As these companies are able to exploit cost advantages by processing different orders in a single run, customers often outsource AM prototypes production to service providers, thus avoiding investment in machinery and equipment.

A wide portfolio of AM technologies is usually offered by these companies, either because they own different machines or they network with partners to provide the processes they lack of.

According to their business model, it is possible to identify the following needs:

- low machine costs, to be able to purchase a wider range of machines. However, an excessively low cost may disrupt the economic barriers to other entrants in the sector, and push OEM (Original Equipment Manufacturer) companies to produce the components themselves;
- low machine maintenance costs;
- high machine versatility, both in terms of different shapes produced and materials that can be used for manufacturing;
- low cost of raw materials.

2.2 Direct competitors

There are a number of system manufacturers present in the sector, who have already invested heavily in AM technology, developed a strong know how in the production process, and created relationships with suppliers and client. A few key players, namely *3D Systems*, *EOS*, *Trumpf*, *Arcam*, witnessed the birth and early development stages of AM and now virtually control all the core patents necessary to manufacture and sell metal 3D-printers. These firms are willing to hold or increase their market share, to take advantage of the expansion of AM, expected to grow at a tremendous pace, by raising market barriers in order to prevent new players (as *Prima Industrie*) from entering the sector.

2.3 Indirect competitors: companies in the metal supply chain

At the present moment, metal AM coexists with traditional manufacturing techniques as its range of applications is mainly limited to rapid prototyping. However, the opportunities offered by AM can strongly reduce the market share of traditional metal manufacturers. This would result in a shrinkage of a huge sector that spans from metal ingot suppliers to tool machines manufacturers, and even in the disintermediation of some players. A way to reduce their hostility towards this disruptive innovation is designing AM machines that can be effectively integrated with tool machines.

2.4 Suppliers

Metal powders suppliers According to *Wohlers' Report* [4], revenues from metal material for AM grew of 38.3% between 2011 and 2012, from 18 million USD to an estimated 24.9 million USD. Metal powder business is an highly profitable one: the same amount of material in the form of powder is sold at as much as ten times more than in the form of ingots. For this reason, machine suppliers are keen to enter this business.

Powder suppliers aim at rising their prices as much as possible, but they are limited by the possibility of machine users entering the sector, because of the low technological complexity of setting up a powder production facility: if the price exceeds a certain threshold it becomes economically convenient to do so. In order to prevent clients from switching to another powder supplier, often, AM systems manufacturers often sell machines paired with their powder.

3D-printing software developers Virtual is the keyword for AM. The real potential of this technology is the possibility to build any geometry that can be virtually modeled with a 3D CAD software. The only limit is human ability to imagine and design new shapes and structures. The AM technology would not exist without the computers and its evolution is strictly linked with the future development of these programs that will have to better support the entire design process. Software developers are looking for a technology with high IT content like metal AM which allows them to develop new design and management tools.

Component suppliers At the heart of almost all metal 3D-printers there is a high power laser source. Therefore, the development of AM is an opportunity for companies manufacturing those high-value component to expand their customer base.

2.5 Public institutions

European Union is willing to invest in AM technology as it would allow bringing in new quality jobs in Europe, reversing the present trend of production shift towards low wage countries. Aiming to drive smart, sustainable, and inclusive economic growth together with jobs creation, *Horizon 2020*, is the biggest research and innovation program ever conceived in the EU, with 80 billion Euros of funding available over the course of 7 years (2014-2020). AM also meets the EU's needs for greener production and sustainable development. On a narrower scale, the Italian government and local communities share the European goals and commitment for economic, social, and environmental development.

In the long term the widespread of AM will result in the creation of highly qualified jobs. However, in the short term, its introduction could lead to a reduction of the demand of low-skilled workforce. Therefore, trade unions could strongly go against the introduction of this technology.

Universities and research institutions carry out innovative research activities in AM and related fields. In particular, *PPP Lab* and *IIT* of Turin are strongly working in this sector, the former focusing on the development of new laser sources, the latter, instead, on new powder materials to use as printing medium.

2.6 Standard-setting bodies

AM standards are under development by *ISO TC261* and *ASTM F42* committees. ISO is a non-governamental and non-profit Swiss-based organization promoting worldwide proprietary, industrial and commercial standards, while *ASTM* is another international US-based standard setting body. Their objective is to be recognized as the world leading standard setting bodies, ensuring that products and services are safe and reliable. In order to fund their activities, ISO sells standards, but it does not provide certifications, which are outsourced to accredited or non-accredited companies, while *ASTM* provide testing facilities and certifications.

The development of standards in the AM industry is a unique opportunity to boost the adoption and growth of this technology. For a successful implementation of standards in the AM field, these committees need to use a common lexicon and set similar requirements for testing and process quality certification.

Chapter 3

Requirements

The overview of the stakeholders involved in metal AM presented in the previous chapter is fundamental for what is analyzed in the current one, namely the requirements of the next-generation metal 3D-printer. Following an outline of the method employed for the requirements elicitation, the needs of the various stakeholders are pointed out. Such needs are then translated into requirements, which are classified into four categories (human-based, functional, corporate and regulatory requirements).

3.1 The requirements elicitation process

In order to identify the different stakeholders' requirements (summarized in Tab. 3.1), a set of activities has been carried out. Firstly the team has gathered information and material about the AM topic, starting from the SoA analysis of the technology. Material, which was partially provided by tutors, included books, papers, scientific articles, web searches and patents.

After the first documenting phase, whose objective was essentially to build a common lexicon, each team member went deeper in examining the aspects of the project closer to his/her competence area, trying to understand the particular requirements in that field. This lead to drafting a technical report featuring an analysis of: intellectual properties, common AM processes, existing AM machines, currently employed metal powders, fields of application, AM software, costs and economics. This document proved to be an effective tool to understand the characteristics and the main criticalities of current AM technologies, and therefore the needs that have to be satisfied by a new AM technology.

The requirements elicitation process also consisted in interviewing institutional stakeholders and companies currently that are employing metal AM or are planning to use it in the near future. In particular, to assess the needs of public institutions, a visit to the laboratories of *IIT* in Turin was arranged. This allowed the team to speak with some technicians and learn from their experience what are the requirements/limits of this kind of machines according to the purpose of their use.

In addition to this, the requirements analysis was also supported by the visit of the headquarters of *Prima Industrie*, during which the team better understood the characteristics that AM technology has to satisfy in order to evolve from mere prototyping applications to a competitive manufacturing technology. This visit was followed by a series of interviews to three different companies: *Avio Aero*, *Medacta*, and *Sinteaplustek* operating in the aerospace and biomedical sectors.

	REQUIREMENTS			
Stakeholder	**Human-Based**	**Functional**	**Corporate**	**Regulatory**
End users	Usability, reduced operator's work burden	Design freedom, capability of manufacturing functionally graded parts, production of lightweight components, surface finishing, low residual stresses, higher building volumes, reduced tolerances, improved mechanical properties, extended range of alloys	Short pay-back period, NPV>0, reduced material waste, economical feasibility also for short-runs, reduced time-to-market	
Direct competitors			Preservation of the competitive gap	
Indirect competitors		Integration of AM into traditional machining centers	Preservation of the market share	
Suppliers		Standardization	High profitability, customer lock-in	
Public institutions	Environmental sustainability, creation of highly-skilled jobs		Increase of firms' competitiveness	Preservation of the competitive gap

Table 3.1: Main requirements of the different stakeholders involved in the metal AM sector.

3.1.1 End users

To elicit end users' requirements, three companies belonging to the aerospace and biomedical sectors were interviewed: *Avio Aero*, *Medacta*, and *Sinteaplustek*. They are already employing metal 3D-printing, therefore they provided the team valuable information about the challenges that they are facing with the current technology and the criticalities of metal AM that need to be addressed.

Avio Aero In this section, the *Avio Aero* case study is presented, discussing how and why this company has approached to AM technology, assessing its potentials and its limits. All the data shown were obtained by interviewing the plant product leader during the team's visit to their facility located in Cameri (NO, Italy) in March 2015.

Avio Aero is an aeronautical company controlled by *GE Aviation* that is focused on the design and manufacturing of components and systems for both civil and military aviation. It operates mainly in Italy, where it employs more than the 80% of its workforce, but also in Poland, Brazil and China. Among its production plants, the one located in Cameri is the most innovative one as it is the biggest facility in the world employing only metal AM.

The aeronautical division of *Avio S.p.A.*, a company founded by *FIAT* devoted to the development of solutions for aerospace, has focused its attention on the design of high performance TiAl alloy turbine blades for civil aviation. This particular alloy has interesting mechanical properties as it offers the same performances of more traditional materials like Nickel superalloys, but at half of the weight. However, the casting process of this material is very challenging and therefore the manufacturing procedure requires an innovative approach in order to be used with reasonable yields.

Avio employed AM for the first time to print plastic models for traditional lost-wax casting. However, this procedure proved to be too costly and has quite low yields due to reliability issues caused by inclusions and pouring defects that unacceptably reduce blades mechanical performances. In 2004, *Avio* started considering metal AM as an alternative to foundry. However, the choice of the particular AM technique to adopt among the few available possibilities (namely the laser and the electron beam powder bed technology) was driven by the necessity to obtain components with low residual stresses. Therefore, the production process had to be characterized by low thermal gradients and a hot chamber to relieve tensions. Such requirements led to the choice of *Arcam* and their proprietary electron beam technology.

In 2013 the aeronautical division of *Avio* was acquired by *GE* and renamed *Avio Aero*. The American company heavily invested in the newly acquired business, building the biggest AM facility in the world in Cameri.

Turbine blades can be manufactured mainly using two alloys: TiAl or Nickel superalloy. The former material ensures high performances at low weight, but is extremely difficult to be employed in investment casting, resulting in production yields as low as 10%. Nickel superalloys, instead, can be easily cast, but their density is 40% higher. Using AM, TiAl blades production can reach yields as high as 87%, thus breaking the trade-off between weight and cost.

In the Cameri plant AM has completely replaced traditional foundry. Blades are designed using *Magics*, a *Materialize* software, and directly manufactured. The production is controlled in real time through *Streamics* in order to abort printing in case of a faulty part, thus minimizing material waste. TiAl powder is internally manufactured using a vacuum induction melting gas atomizer starting from billets, minimizing in this way material cost.

The high production control required by the aeronautical sector has been achieved through a long lasting trial-and-error approach. As a matter of facts, as samples can be quickly manufactured, FEM

(Finite Element Method) production analysis is not necessary.

The present limits of the AM technology are mainly related to the dimensions of the building volume, which reduce the maximum dimensions of feasible components and the number of parts that are produced in a single run. Therefore machines with increased dimensions need to be introduced. Moreover, machines need to increase their output: current machines were developed by researchers (with downtime during the process), but they are now adopting design criteria typical of machine tools (cutting downtime and boosting productivity).

Avio Aero forecasts to be the dominant player in the AM aerospace industry in the future, thanks to its intellectual property and experience accumulated over the years. The feasibility of AM in production processes is strongly related to its costs. In the experience of *Avio*, the two main cost drivers are machine depreciation, that can make up to the 60% of the total cost, and raw materials purchase, which can vary from 20 to 40% of the total. Metal powders can be either internally produced or outsourced: *Avio* found more convenient to set up its own powder gas atomization facility. Other cost drivers are consumables, which amount to about 10% of the final cost, and energy to run the process and maintenance make up another 10%. Maintenance is usually carried out in the form of total care contracts, in which the machine producer provides both assistance and spare parts. Finally, manpower constitutes the final 10% of the cost.

Medacta In this section, the *Medacta* case study is presented. This latter is a Swiss-based biomedical company, headquartered in Castel San Pietro (a district of Mendrisio) and operating in 30 countries, which the team interviewed during a conference call in May 2015. The company is a world leading manufacturer of orthopedic implants, neurosurgical systems, and instrumentation.

Their current implants portfolio comprises knee, hip, and spinal systems. The materials employed are metals and polymers, processed either with traditional or additive approaches. AM is already exploited at the commercial stage for polymeric products, in order to manufacture patient specific implants: they 3D-print more than 10,000 polymeric guides for *MySpine*, *MyHip*, and *MyKnee* systems per year. Metal parts are still manufactured with traditional technologies, even if the company is exploring the possibility to use AM for Titanium, Chromium-Cobalt-Molybdenum, and stainless steel components.

According to *Medacta* experience, AM is a viable and competitive technology whenever complexity is the issue: anatomically shaped components, customized products, parts with porosity gradients, and devices for bone revision or reconstruction are easily produced with an additive process. In addition to this, AM is advantageous for extremely short-run productions, with few or even one single component to be manufactured.

However, at the present state AM is still costly for large-scale production, and has several limitations: it is not possible to obtain multi-material components, high quality surface finishing, and precise tolerance values for mechanical coupling. Moreover, mechanical properties of additively manufactured components, namely fatigue resistance, are poorer than those of forged parts.

Sinteaplustek In this section, the *Sinteaplustek* case study is presented, discussing the company experience with AM technology. All the data shown in this chapter were obtained interviewing two of the company's engineers, during the visit of the team to their building located in Assago (MI, Italy).

Sinteaplustek is a small biomedical company focused on the design and manufacturing of prosthetic components which operates mainly in Italy, although it is present also in Miami. Since the key requirements for biomedical parts are biocompatibility, lightweight, and elasticity, the material usually chosen for such applications is the Ti6Al4V Titanium alloy, which combines good mechanical properties with biocompatibility when traditionally manufactured. However, such material shows poorer mechanical properties if additively manufactured, namely a lower elasticity, due to lower density and extremely high heating and cooling rates during deposition. Other issues delaying the use of AM are component repeatability and limited process productivity.

The company experience with metal AM is fairly limited, with an additively manufactured hip implant project, with a special superficial mesh studied to boost osseointegration, which they have patented. Although osseointegration plays a crucial role in hip implants performances, market figures and the company experience show that excessive integration is met with mistrust by surgeons due to the additional difficulties introduced in case of further interventions to remove the prosthesis. Moreover, hip implants do not require extreme customization to match the patient's anatomy, as they are currently produced in a range of different sizes. As a consequence, although such components are the most successful AM product in the biomedical sector (considering the dental sector as a separate sector), *Sinteaplustek* chose not to produce hip implants with AM technologies.

In the near future, the company is willing to use AM only for those applications that can not be realized with other technologies, because of the limits previously mentioned, which prevent AM from replacing traditional manufacturing. In particular, AM has the potential to play a fundamental role when associated to extreme complex geometries and short run productions. Such conditions are especially met in the case of custom components manufactured for single patients affected by tumors or traumas.

As their main competitors are large multinational players, *Sinteaplustek* has to pursue a competition model based on cutting edge innovation, rather than basing it on price. Therefore, the vision of *Sinteaplustek* for the future involves AM prosthetic components, provided that advances in the field of bio-printing are achieved, enabling integration of growth factors and osteoblasts in the component.

3.1.2 Direct competitors

As previously pointed out in the section regarding stakeholders, a lot of companies are already manufacturing metal AM machines. However, their technology is based upon patents registered as long as 20 years ago. Therefore, they will expire soon. For this reason, direct competitors are looking for a way to protect their own market share, even if new companies will enter into the market exploiting previously protected intellectual properties. Thus, incumbents need to strongly invest in R&D to preserve the competitive gap.

3.1.3 Indirect competitors

As depicted in Fig. 3.1, although the present dimension of the AM market is only a small fraction of the machine tool one, the expected growth of AM can possibly shrink their business. Companies like *DMG Mori Seiki* and *Ibarmia* are developing machines that combine AM together with subtractive manufacturing. This approach allows them to exploit their expertise in the field of machine tools, while gradually introducing the revolutionary potential of AM.

3.1.4 Suppliers

At the present moment, metal powders employed in 3D-printing account for as much as 26% of the total cost of the manufactured part [3]. Therefore, powder suppliers play an important role in defining the future of the metal AM industry. Standardization of powders in such a way that different manufacturers can supply the same machine is desirable for companies that are planning to enter into the market and

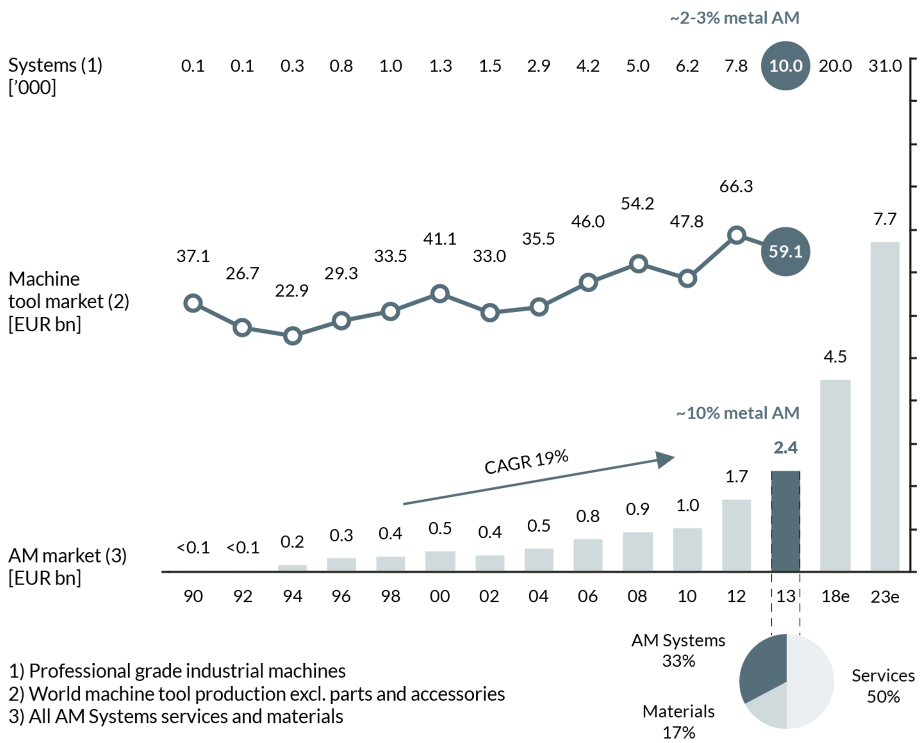


Figure 3.1: Expected growth for the global AM market compared to the machine tool market [3].

can lead to a reduction of printing medium cost. However, some 3D-printer manufacturers like *EOS* force end users to employ specific powders, locking in the consumer and keeping high the price of raw materials.

3.1.5 Public institutions

Public institutions aim to increase competitiveness of the industrial sectors at a regional and European scale, fostering the creation of high-skilled jobs and protecting at the same time the environment. In order to meet these requirements, a suitable environment needs to be created, such as the *Horizon 2020* program. Moreover, AM has to comply with laws regarding the working place safety.

Part III

State of the art

Chapter 4

AM processes

In this chapter, the two main approaches to metal AM are presented: Powder Bed Fusion and Direct Energy Deposition. Each process is described in general terms, along with the underlying physical phenomena. As the nomenclature employed by the various machine manufacturer may be misleading, each section uses the terminology introduced by J. P. Kruth in [10] and separately presents the one used by the industry.

4.1 Powder Bed Fusion

"Powder Bed Fusion (PBF) is a process by which thermal energy fuses selective regions of a powder bed" [4]. Each company and university has developed its own proprietary technology, branding it under different names. However, they all share similar characteristics as they all have a thermal source to melt metal powder, a control system to select the powder bed region to melt and an apparatus that evenly adds powder layers.

PBF was among the first commercially available AM processes [2], thanks to the work carried out during the 1980s by University of Texas master degree student Carl Deckard. These studies lead to the development of the first commercially available laser-sintering apparatus in 1992 [12].

4.1.1 Process description

PBF processes print 3D parts by sintering and/or melting thin layers of powder that are evenly spread by means of a leveling roller. Prior to the start of the printing process, the entire printing medium is preheated in order to minimize non-uniform thermal expansion or contraction that could wrap the manufactured part. The build chamber is filled with inert gas or it is held under vacuum in order to prevent powder oxidation.

Fig. 4.1 shows the simplified schematic of a PBF 3D-printer. In this example, the energy source is a laser beam that is controlled using a deflection system made up of galvano mirrors, but it can be, as discussed in the following paragraphs, an electron beam properly deflected by means of the magnetic field generated by control coils. After the energy source has fused the first layer of material, the build chamber is lowered by the thickness of one layer and the leveling roller adds and evenly spread a new layer of material powder. The process is repeated until the part is completed.

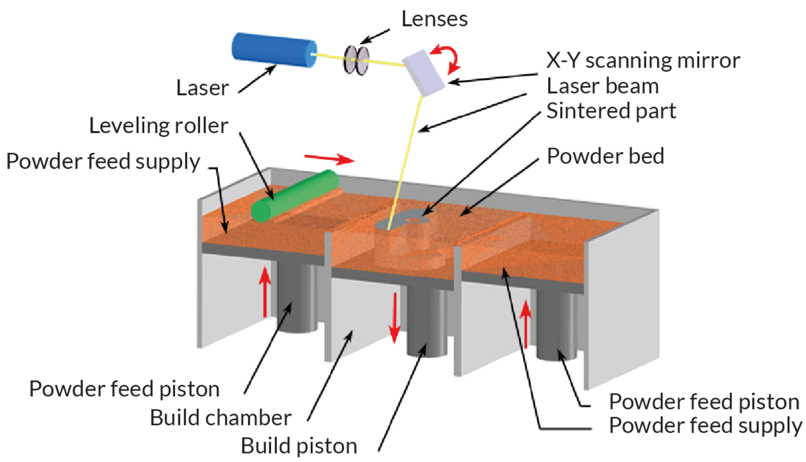


Figure 4.1: Schematic representation of a PBF machine [11].

Each AM machinery manufacturer named its own PBF technology using a different terminology from competitors, even if the underlying physical principle is the same. Thus, for the sake of clarity, first the various processes are discussed using the classification described in [10], as it is based not on proprietary names, but on the physical phenomenon that binds the metal powder. In paragraph 4.1.2, instead, an overview on the commercial nomenclature is discussed.

According to [10], there are 4 processes that are employed in PBF technologies:

- Solid-State Sintering;
- Chemically-Induced Binding;
- Liquid-Phase Sintering;
- Full Melting.

Solid-State Sintering

"Solid-State Sintering (SSS) is a thermal process that occurs at temperatures between $T_{Melt}/2$ and T_{Melt}, where T_{Melt} is the melting temperature of the material. Various physical and chemical reactions occur, the most important being diffusion" [10] of material from one powder particle to the adjacent one to lower the free energy.

The main advantage of SSS is that it can be employed in a large variety of materials. However, this kind of sintering process is extremely slow and it requires the building chamber being preheated at temperatures as high as 900 °C. Furthermore, parts produced using this technology are highly porous and often require thermal treatments after printing.

It is important, however, to keep in mind that SSS is present also in PBF processes that employ other primary fusion mechanisms. As a matter of facts, SSS is thermally activated and high temperatures are reached also in the other cited sintering and melting mechanisms [10], thus leading to both desired and undesired effects. On one hand, secondary sintering reduces part porosity and increase tensile and compression strength of the powder bed. On the other, instead, it leads to a more difficult recycling process as it increases the average diameter of the metal powder.

One of the main producer of AM machines based on this process is *Phenix Systems*, France.

Chemically-Induced Binding

As Chemically-Induced Binding (CIB) is a process primarily used in ceramic-based 3D-printing [2], it is briefly discussed in the following. This sintering process is based on a thermally activated reaction that yields to a by-product capable of binding together the powder; it produces highly porous parts that require further thermal processing [10].

Liquid-Phase Sintering

Liquid-Phase Sintering (LPS), also known as Partial Melting, is the most versatile mechanism for PBF [2]. This process melts only a fraction of the powder metal. The melted part acts as a binder, gluing together the unmelted material, which gives structure to the final part.

Binder and structural material can be distinct or indistinct. In the former case, the two components can be separate particles, present in the same particle thus making a composite particle or the particles can be coated by binder. These approaches produce low density and poor quality parts when used to print metal components. In the case of indistinct binder and structural material, instead, the single particle is partially melt and thus metal powder sticks together. This is the process used in early *EOS* DMLS machines.

Full Melting

Full Melting PBF processes differ form other technologies as the heat source is employed in such a way that it completely melts the selected area on the powder bed. This approach allows the production of near full dense parts that do not require long thermal treatments after printing [10]. Furthermore, it assures that the final product has mechanical properties that match or even beat those of conventionally manufactured parts [13], as "thermal energy of subsequent scans of a laser or electron beam is typically sufficient to re-melt a portion of the previously solidified solid structure" [2].

Full Melting presents several challenges in terms of characterization of the material used as powder bed as each given metal requires a particular combination of scanning speed and applied power. As a matter of facts, on one hand excess heat can lead to spherification of the liquid melt pool that eventually causes track instability, on the other, if the applied energy is not enough, layers will not melt one on top of the other [10].

There basically exist three different approaches to Full Melting: [10]

- single component, single material powder: mainly Titanium;
- single component, alloyed powder particles: *Fraunhofer Institute of Laser Technology* (ILT) is carrying out studying on stainless steel;
- fusing powder mixture: the powder bed can be partially or fully melt.

4.1.2 Proprietary technologies

Direct Metal Laser Sintering / Selective Laser Sintering

Direct Metal Laser Sintering (DMLS) and Selective Laser Sintering (SLS) are two names used respectively by *EOS GmbH*, Germany and *3D Systems*, USA (formerly *DTM Corp.*) to refer to their own PBF technology. The difference in the two approaches lies in the fact that *3D Systems*' machines are designed to sinter a very large variety of materials, whereas the German manufacturer designed material-specific devices [2].

3D Systems' top-level machines are branded under the name *ProX* and all employ high power neodymium doped fiber lasers. In order to better distinguish them among plastic powder devices, they recently re-branded their metal sintering technology "Direct Metal Printing".

DMLS has been developed in cooperation by *Rapid Product Innovations* (formerly *Electrolux Rapid Development*, Rusko, Finland) and *EOS*. The basic principle of DMLS is to fabricate metal parts directly in a single process reducing shrinkage to a minimum [14]. For this reason, DMLS is considered a true net-shape process.

The first system of this kind became commercially available during 1998 under the name of *EOSINT M 250 Xtended* as an evolution of *EOSINT M 250*, which was sold starting from 1994 and was capable of sintering just plastic powder [12, 2]. This system was based on a liquid-phase sintering approach that required no preheating. However, porosity of the end product was not acceptable, so *EOS* moved in 2004 to a full melting technology (which is described in the following section), maintaining the DMLS name [2].

Fraunhofer ILT, which collaborated with *EOS* during the 90s, worked together with *Trumpf AG* during the beginning of 00s, thanks also to some patent cross-license agreements signed with *EOS*. Thus, *Trumpf* started selling the first AM machines in 2003 that were based on the same DMLS technology with some slight differences. For instance, the heating source employed was a disc laser. *Trumpf* also re-branded the process "Laser Forming" [12].

Selective Laser Melting

Selective Laser Melting (SLM) is the name employed by *SLM Solutions GmbH* and *ReaLizer GmbH* to refer to their proprietary technology based on full powder melting [4]. Studies on SLM started during the first years of the 90s at *Fraunhofer ILT* and lead in 1996 to the registration of the first patent on SLM [15].

Present technology allows the production of parts employing steal, Titanium-, Aluminum- and Nickel-based alloys with powder grain sizes between 10 µm and 60 µm, which allow precisions up to 50 µm [16].

Both *SLM Solutions* and *ReaLizer* use as heat source fiber lasers whose maximum power can be as high as 1 kW.

Electron Beam Melting

In contrast to the previously discussed laser-based systems, Electron Beam Melting (EBM) uses a high-energy electron beam to induce fusion between metal powder particles. This process was developed at Chalmers University of Technology, Sweden, and was commercialized by *Arcam AB*, Sweden in 2001 [2].

EBM presents some technical differences from all other laser-based PBF. As a matter of facts, the printing chamber is not filled with inert gas, but held under vacuum as gas particles can reduce the beam efficiency. Furthermore, it does not require powder preheating, as the electron beam itself is capable of bringing the material at very high temperature. This leads to both advantages and disadvantages: on one hand high temperatures lead to the production of parts that are fully dense and free from residual stress and distortion at a micro level; on the other hand, the product could suffer thermal stresses during the cooling process.

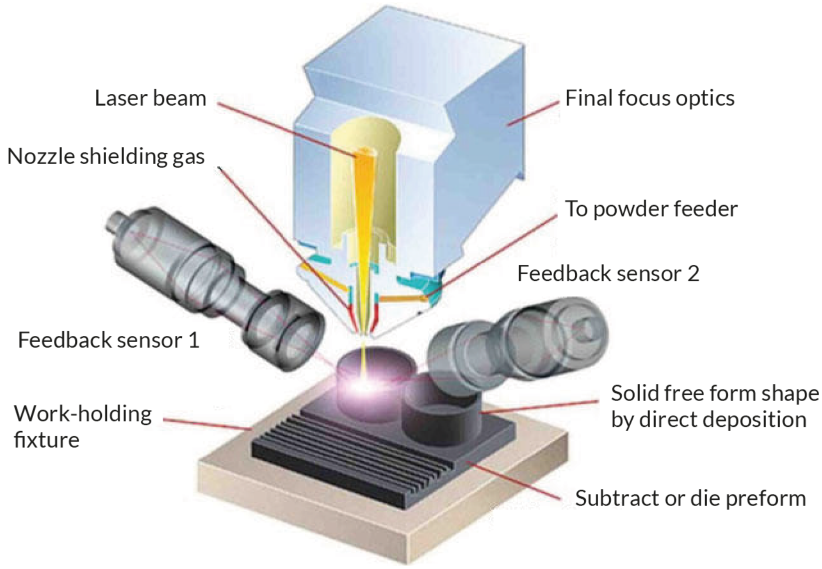


Figure 4.2: Schematic representation of a DED machine [17].

4.2 Direct Energy Deposition

4.2.1 Process description

"In the Direct Energy Deposition (DED) process, focused thermal energy is used to fuse materials by melting as the material is being deposited" [4]. Fig. 4.2 shows a schematic representation of a DED machine. Metal is melted either in flight or upon injection into a molten puddle, and is deposited onto a deposition stage. Scanning the printing head or moving the deposition stage, the final part is built layer by layer. As in PBF processes, the energy source can be a laser beam or an electron beam that creates a mobile molten pool on the substrate in which the new material powder is injected.

A laser deposition system generally comprises: a powder material feeder, a material delivery system, a laser, a deposition stage and a computer controller [18]. The deposition process is performed, like with PBF technologies, in a chamber filled with inert gas in order to prevent metal oxidation and/or ignition and to promote fill density [18]. The stream of metal powder has to be constant and accurate, otherwise material accumulations or deficiencies will add up layer by layer, compromising the final result. This is achieved using carrier gases to transport powder from the feeder to the delivery system and using sensors that acquire data to be fed in the control system, which also regulates the position of the deposition stage and the energy source output power. Furthermore, to ensure the stability of the molten pool, thermal cameras are often used as a feedback system to monitor the process [17]. Cooling and consequent solidification is achieved simply by thermal conduction through the part and the substrate.

A wide variety of materials can be employed in DED. In particular, it allows the adoption of high-melting-point alloys that cannot be used in PBF technologies.

Until now, AM machines based on this technology have had limited success due to their extremely high cost with respect to PBF-based devices [4]. However, they have unique features that make this technology promising for the future. As a matter of facts, DED allows deposition of different materials on the same parts, making functionally graded parts possible. Furthermore, it allows repairing, re-manufacturing, cladding and hard-facing of preexisting parts [17].

4.2.2 Proprietary technologies

Laser Engineered Net Shaping

The main proprietary technology based on DED is known as Laser Engineered Net Shaping (LENS). It was "originally developed at *Sandia National Laboratory*, USA, and further developed and marketed by *OptoMec*, USA, is the most popular commercial RM process capable of handling a variety of metallic powders including Ti" [19].

OptoMec machines use lasers of power ranging between 500 W and 4 kW and Argon is employed inside the printing chamber to prevent material oxidation. They employ feedback systems to control powder mass-flow, deposition region temperature and laser position in order to ensure that the focal plane of the laser is at constant distance from the deposition surface [18].

Direct Metal Deposition

Direct Metal Deposition (DMD) is a technology developed thanks to the collaboration between University of Michigan and *POM Group*, USA (acquired by *DM3D* in 2013) [20]. The characteristics that differentiate DMD from LENS is a patented closed-loop feedback control system that monitors not only the geometry of the molten pool, in order to ensure the production of near-net parts, and sense the material temperature to control the heating and cooling rate dynamically adjusting laser power, but also provides a "control of dimension during deposition process" and "has the potential to be adapted for controlled composition and microstructure" [21].

Chapter 5

Metal AM history and main patents

In this chapter, the history and the development of laser metal AM are investigated. The knowledge of how AM has evolved over the years is fundamental, as it allows to understand who presently owns the intellectual properties of the innovations that made 3D-printing possible, therefore it is a key aspect to understand how the market will evolve and how a new player can enter into it.

5.1 AM: a new idea

The first commercial laser metal AM systems came out in 1995, but, as can be seen from the timeline in Fig. 5.1, the process development has a longer history. As a matter of facts, the basic idea of creating parts layer by layer dates back to 1971, when Pierre Ciraud, a French inventor, filed a patent describing manufacturing of three-dimensional objects by consolidating powder on a substrate using an energy beam, enabling also the realization of complex shapes. However, this patent was not very specific and the technology presented was more similar to modern DED systems rather than PBF ones. In the end, the idea was ahead of its time as technologies necessary to the process, namely the lasers and computers, were in their early stages of development [14, 22].

A few years later, in 1977, Ross Housholder, an American engineer, filed a patent (then granted in 1979) titled "Molding process", describing a process similar to modern SLS, as Fig. 5.2 shows. Unfortunately, lasers were excessively expensive at that time, therefore the technology was tested in a form which did not require the use of a laser. No commercialization followed, until *DTM Corp.* discovered this patent in 1992 and licensed it [14, 23, 24, 22].

5.1.1 Stereolithography: the first AM commercial process

During the 1980s parallel work in Japan, France and the US led to the birth of the first commercial polymeric AM systems in the world. In May 1980 Hideo Kodama filed a patent application for polymerization of resin in a vat using a single laser approach. A dual laser approach dating back to the 1960s had been thoroughly investigated, but it had never resulted in a commercial system. The single laser approach is a key aspect of Stereolithography (SLA), but unfortunately the patent application by Kodama expired due to lack of funding for the necessary examination stage. In October of the same year

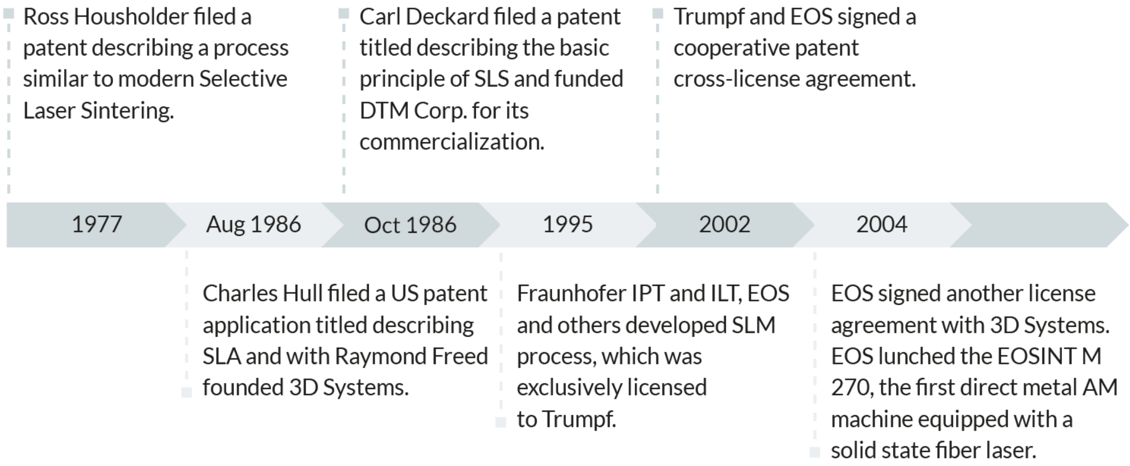


Figure 5.1: Timeline of the AM evolution.

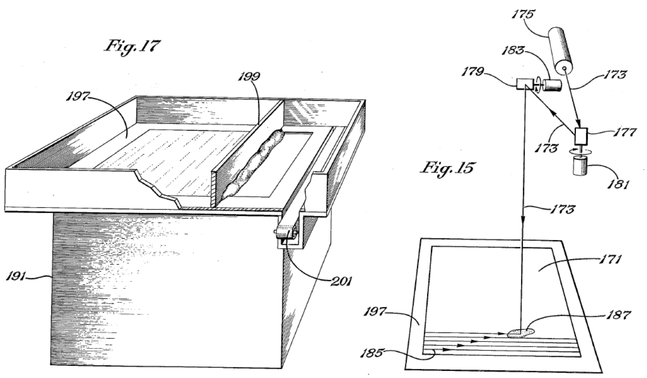


Figure 5.2: Schematic representation of the process illustrated by Housholder in his patent application [23].

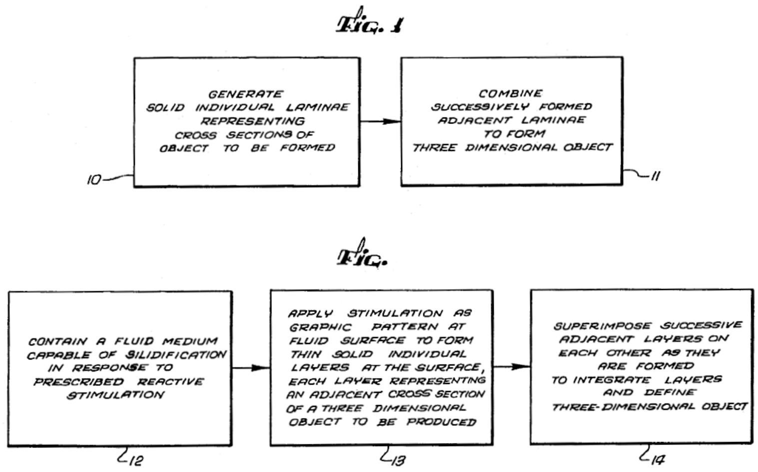
and November 1981 Kodama published several papers detailing his experiments, which are likely to be the first evidence of AM in human history.

One year later, in 1982, Alan Herbert, a scientist at *3M Graphic Technologies Sector Laboratory*, published a paper titled "Solid object generation". It described a process exploiting a laser beam focused on the surface of a photopolymer in a vat, with mirrors attached to a x-y pen plotter device. This system was capable of creating basic three-dimensional shapes and was intended as a mean to explore the requirements for a real commercial system. Despite the results obtained by Herbert, *3M* decided not to support the development of this technique [4].

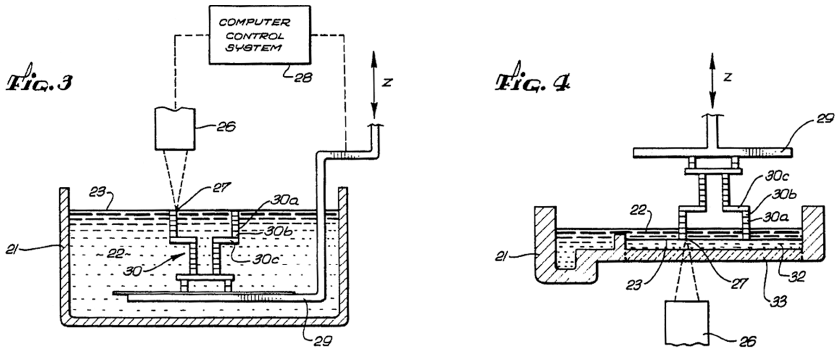
In July 1984 Jean-Claude Andre from the *French National Center for Scientific Research* filed a patent titled "Apparatus for fabricating a model of an industrial part", which was granted in January 1986 and described a single laser approach polymeric AM process. This was later commercialized by *Laser 3D* as a service and the actual AM machines were never sold [4, 14, 2].

In August of the same year, Charles Hull filed a US patent application titled "Apparatus for production of three-dimensional objects by stereolithography", which was granted in March 1986, when Hull together with Raymond Freed founded *3D Systems*. The patent made broad patent claims covering in principle any material capable of solidification, although the process described the use of liquid resins solidified by a single laser (Fig. 5.3(a) and Fig. 5.3(b) respectively describe the workflow and the process as illustrated in the patent) [4, 25, 14, 2, 22].

In Japan, Yoji Marutani researched and developed SLA at the *Osaka Prefectural Industrial Research*



(a) The workflow.



(b) The process.

Figure 5.3: Schematic representations of the process and the workflow illustrated by Hull in his patent application [25].

Institute, independently of Hull's work in the US and then filed a patent application in May 1984 [4, 2].

In 1986 Takashi Morihara from *Fujitsu Ltd.* patented a blade system for SLA to speed up the leveling of the resin in the vat and then another system for dispensing the resin from a slot moving above the liquid surface. This idea remained also for metal power distribution in PBF processes [4].

In late 1987 *3D Systems* started shipping its first beta units to its customers and in April 1988 the first production units were sold. Those were the first commercial AM system installations in the world [4].

The following year Hans J. Langer and associates founded *Electro Optical Systems* (*EOS*) in Germany, an AM company manufacturing SLA machines at first, but that later became a key player in the metal AM landscape [4].

5.2 The birth of metal AM

Starting from the late 1980s different processes for metal AM were developed, with many analogies to the already present polymeric ones.

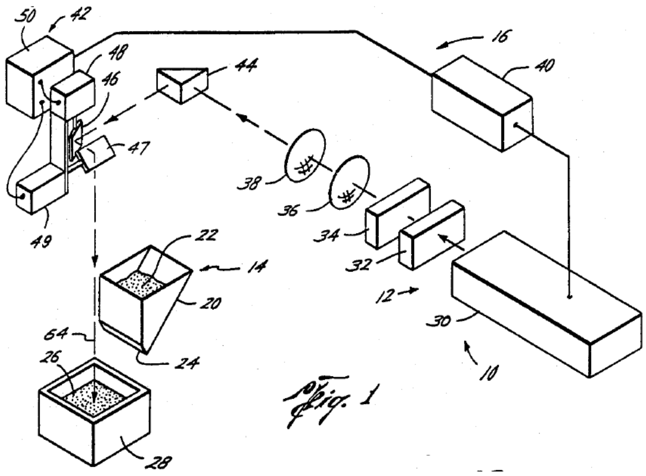


Figure 5.4: Schematic representation of the process illustrated by Deckard in his patent application [26].

5.2.1 Indirect processing

In October 1986, Carl Deckard, a student at the University of Texas, filed a patent titled “Method and apparatus for producing parts by selective sintering”, describing a process similar to that patented by Hull in 1984, but using powders instead of a liquid resin, as Fig. 5.4 shows. The process was nearly identical to the idea illustrated by Housholder in 1979, although in this case the technology had actually been experimentally tested using a laser. At this first stage, no metal powders were used, although a few years later, in the early 1990s, the process was successfully applied to manufacture metal parts through indirect processing. Metal powders coated with a polymeric binder were solidified into a green part using a laser, then the polymeric binder was eliminated in a furnace and the remaining porosity was infiltrated by another metal.

This technology was licensed to *Nova Automation*, a company purposely set up by the University of Texas to commercialize SLS. The company was renamed *DTM Corp.* in 1989. In 1990, after a second round of funding by *Goodrich Corp.*, *DTM Corp.* bought several patents to enlarge its portfolio.

In 1992 the *Sinterstation 2000* was commercialized: it was the first commercial laser sintering system. The second one was the *EOSINT (P) 250* commercialized by *EOS* in 1994. During the same year, Deckard filed another patent concerning SLS, mainly related to powder dispensing and air flow control inside the chamber.

In 2001 *DTM Corp.* was bought by *3D Systems*, which had been its main competitor until that moment [24, 22, 26, 27, 14].

5.2.2 Direct processing

The first attempts to directly process single phase metal powders took place at University of Texas in 1989-90, but they were unsuccessful. However, a few years later, in 1994, first successes were reported by experiments at *Fraunhofer Institute for Production Technology* (IPT) and *KU Leuven.*

In the same year *EOS* started a patent license and cooperation agreement with *Electrolux Rapid Development* for research and development of DMLS. The following year *EOS* installed the first commercial *EOSINT M 250*, introducing the first real commercial use of DMLS for rapid prototyping.

At the end of 1995, a cooperative project by *Fraunhofer IPT* and *ILT*, *EOS* and others on the production of fully dense parts by complete melting of single phase metals led to the development of

SLM, which was patented by *Fraunhofer ILT* [15]. Dr. Dieter Schwarze and Dr. Matthias Fockele formed *F&S Stereolithographietechnik GmbH* to commercialize the process.

In 1997 *EOS* and *3D Systems* entered a key strategic agreement, according to which *EOS* left the field of SLA and acquired exclusive rights to the patent portfolio of *3D Systems* on laser sintering technology, which included many aspects like data preparation (STL file) and exposure strategies.

In 2000 *F&S* started a partnership with *MCP Group* on SLM. Two years later *Trumpf* (which had exclusive rights on the *Fraunhofer ILT* patents concerning SLM) and *EOS* signed a cooperative patent cross-license agreement.

In 2004 *EOS* signed another license agreement with *3D Systems*, gaining access to all relevant patents from *DTM Corp.* and the University of Texas. During the same year *EOS* lunched the *EOSINT M 270*, the first direct metal AM machine equipped with a solid state fiber laser.

In February 2008 *EOS*, *Trumpf* and *MCP* entered a patent agreement regarding SLM and in the same year *MCP* created *MTT Technologies Group* as a spin-off. Two years later this company split into *MTT Technologies Group* (Germany) and *MTT technologies Ltd.* (UK). The English branch was sold to *Renishaw* during the same year, while the German one became *SLM Solutions* in 2011 [28, 14].

Chapter 6

Metal AM machines

In this chapter, the present SoA of metal AM machines is outlined by the results of the survey carried out by the team on the devices currently on the market worldwide. A comparison, based on technical data, has been made among the different manufacturing processes available in this sector: the Powder Bed Fusion (SLS/SLM and EBM) technology and the Direct Energy Deposition one.

For each of the analyzed AM technologies, the most important machine manufacturers currently present on the market have been examined. Both the devices themselves and their outputs have been described, in structural and technological terms, on the basis of few parameters considered to be pivotal for making a comparison among the different manufacturers and summarizing the SoA of the above-mentioned processes.

The data collected through this analysis have been used for obtaining the results shown in Tab. 6.1. For what concerns the SLS/SLM and the DED processes, since several are the manufacturers marketing machines that exploit such techniques, the variation range and the typical value of each parameter, resulting from the analysis of the different devices, have been reported.

As can be seen from Tab. 6.1, forming rooms of AM machines are usually not very voluminous. However, the main manufacturers have brought to market devices of different sizes in order to meet the needs of the customers. Deserve special emphasis those small-sized machines intended for manufacturing parts in the dental and jewelry sectors, which require higher quality compared to that of the components usually produced by means of the AM techniques; therefore, it is easy to understand that devices dedicated to such applications need a design of its own.

Directly depositing the metal powder on top of the underlying layer, the DED technology requires a laser beam of much higher power than that involved in the SLS/SLM processes. This fact implies that the DED way of manufacturing is intrinsically characterized by a higher build rate. The power of the electron beam which *Arcam AB* makes use of can be adjusted within a wide range; as a consequence, the same does the build rate, the values of which lie in between those of the SLS/SLM and the DED technologies.

However, while evaluating the build rate of a machine, it is important paying attention to the fact that this parameter is not only correlated to the beam power, but also to the scanning speed of the beam head and the spot size (in case of SLS/SLM or EBM) or the deposit width (in case of DED). The higher values of the beam power characterizing the EBM and, above all, the DED processes allow the adoption of higher layer thicknesses and spot sizes or deposit widths in comparison with the typical values of the

Manufacturing technology	SLS & SLM	DED	EBM
Machine manufacturers	WuHan BinHu Mechanical & Electrical, Renishaw, Phenix Systems (3D Systems), Concept Laser, EOS, ReaLizer, SLM Solutions, Sisma - Trumpf, 3D Systems	BeAM, InssTek, Optomec	Arcam AB
Forming room (mm)	50 x 50 x 80 - 630 x 400 x 500, typically 250 x 250 x 250	100 x 100 x 100 - 900 x 1500 x 900, typically 650 x 550 x 450	250 x 250 x 400 - Ø 350 x 380
Layer thickness (μm)	10 - 200, typically 50	100 - 1000, typically 400	50 – 200
Build rate (cm^3/h)	1 - 100, typically 20	30 - 180, typically 100	55 – 80
Part accuracy (mm) over 100 mm	± 0.02 - 0.1, typically ± 0.05	± 0.1 - 0.5, typically ± 0.3	± 0.2
Detail capability (mm)	< 0.1 - 0.3, typically 0.1	0.5 - 1.0, typically 0.6	0.25
Maximum part density	99 - 100 %, typically 99.5 %	99 - 100 %, typically 99.5 %	approx. 100 %
Part surface finish Ra (μm)	3 - 20, typically 10	4 - 9, typically 7	10 – 20
Laser/beam power (W)	50 - 1000, typically 400	300 - 4000, typically 1500	50 – 3500
Laser/beam spot size or deposit width (μm)	10 - 700, typically 100	600 - 4000, typically 1800	180 – 1000
Maximum scan speed (m/s)	2 - 15, typically 7	0.06 - 0.17, typically 0.10	8
Protective gas	Argon or Nitrogen	Argon or Nitrogen, typically Argon	none (vacuum)
Approximate price (€)	120'000 - 1'500'000, typically 500'000	230'000 - 1'000'000, typically 600'000	630'000

Table 6.1: Results of the survey on the metal AM machines currently on the market.

SLS/SLM technology. For what concerns the scanning speed of the beam head, this is obviously much lower with the DED technique.

In any case, machine manufacturers usually choose the values of the above-mentioned parameters finding a compromise between the requirements of productivity of the devices and the geometric, microstructural and mechanical features of the manufactured parts. Although being characterized by a lower productivity, the SLS/SLM process proves to be clearly above the other technologies in terms of accuracy and detail capability of the produced parts. On the basis of these parameters, the EBM process once again ranks in between the two laser-beam techniques, indirect and direct respectively.

A feature common to all the three AM technologies is the fact that it is possible to manufacture parts whose density can reach the one of the monolithic solid, that is 100%. Moreover, the poor surface finish of the parts produced by means of all these techniques, despite being slightly better with the DED one, requires, in any case, the components intended to be mechanically coupled in the final assembly to undergo post-manufacturing processing in order to improve this geometric feature.

While the SLS/SLM and DED machines need the forming room to be filled with inert gas, in the case of the EBM technology ultra-vacuum conditions are required. This fact slightly decreases the complexity of the devices, since a dedicated circuit for the supply of gas (which normally has to be stored and filtered) to the manufacturing chamber has not to be included.

Regarding the prices of the machines, it is possible to say that they tend to increase with the size and the productivity of the devices.

To sum up, the powder-bed AM technologies, although lacking few of the processing possibilities available with the DED technique (such as repairing or cladding parts and developing designed materials [17]), present themselves as the best from the point of view of the quality of the manufactured parts. As the values of the considered parameters demonstrate, despite being less widespread among the AM machine manufacturers and having been developed more recently, the EBM technology turns out to be perfectly comparable to the SLS/SLM processes in terms of quality of the outputs and prices of the devices, even showing a higher productivity [29].

Chapter 7

Materials

In this chapter, the metallic materials available for the different laser AM processes, the characteristics of the metal powders currently being used and their actual limitations, together with the future development needs, are discussed.

7.1 Materials available

The first materials available were used for indirect processing, consisting of debinding, sintering and infiltration at different temperatures. These materials were:

- *RapidSteel 1.0* (1996, by *DTM Corp.*, now part of *3D Systems*), made of carbon steel powder coated with a thermoplastic binder and using Copper as infiltrant material;
- *RapidSteel 2.0* (1998), consisting of stainless steel powder coated with thermoplastic and thermoset binders and exploiting bronze as infiltrant;
- *Laserform ST-100*, which was AISI 420 stainless steel powder (available also with H13 and A6 tool steels) mixed with bronze as infiltrant [2].

Today, the materials available for laser AM of metal powders are [4]: tool steel, stainless steel, commercially pure Titanium, Titanium alloys, Aluminum alloys, Nickel-based alloys, Cobalt-Chromium alloys, Copper-based alloys, Gold, Silver.

Thanks to the high cooling rates present in laser AM, there are several microstructural advantages:

- absence of diffusion controlled solid-state phase transformations;
- formation of non-equilibrium phases;
- formation of very fine microstructures with extremely reduced segregation;
- formation of very fine secondary phase particles.

Showing a fine grain structure, AM parts often exhibit superior yield and tensile strength than conventionally manufactured components, but lower ductility. This is confirmed by Fig. 7.1, which shows the mechanical properties of several materials additively manufactured.

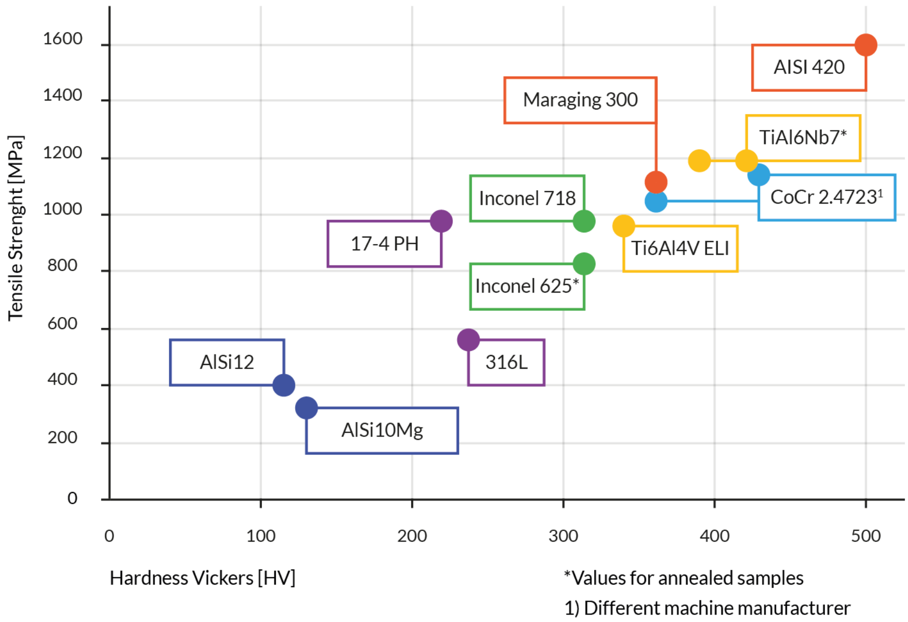


Figure 7.1: Material properties of several additively manufactured alloys [30].

Research in the field of metal powders for AM is very active. Patents regarding metal powders for AM are continuously registered (e.g. steel powder by *EOS GmbH* in 2008 [31], stainless steel powder by *The Boeing Company* in 2011 [32], Silver-based powder by *Legor Group S.p.A.* in 2013 [33], alloy for dental prostheses by *The Argen Corporation* in 2013 [34]).

The materials used in AM are characterized according their absorptance, surface tension and wettability and viscosity.

7.2 Powders for laser sintering

There are several types of powder systems available for laser sintering: multicomponent and single phase systems.

Multicomponent systems can be divided into two classes: systems consisting of structural metal and metallic binder (which exhibit a big difference in melting points) and alloyed Iron mixtures, with chemical composition corresponding to a certain type of steel [17]. In the former case, the solidification mechanism exploited is liquid phase sintering [35]. Moreover, laser energy density necessary for densification is determined by melting points of the components and their absorptance [35]. When present in the alloy, Phosphorous and its compounds can act as deoxidizers, preventing balling phenomena [36]. However, final components will suffer from inherent intercrystalline weakness due to difference in chemical/physical properties of binder and structural metal [17].

Single phase systems consist of prealloyed powders [17]. Densification is determined by the Laser Energy Density (LED), a parameter depending on laser power, scan speed, and hatch distance. LED must be greater than a minimum threshold, but it should not be excessive in order not to influence negatively the mechanical properties [37].

Mechanical properties of laser sintering manufactured components are usually better than those of the corresponding material manufactured conventionally [38].

7.3 Powders for laser melting

Pure metal powders are available for laser melting, but they are not the main research focus due to relatively weak mechanical properties and poor oxidation/corrosion resistance [17]. Nevertheless, noble metals are of interest in fields where mechanical properties are not the main concern, like jewelry. Gold is used in laser melting processes, although it exhibits a narrow process map (plot of the processing results in a laser power-scan speed space) optimal region for good melting, due to its high reflectivity. Moreover, laser melted Gold components exhibit better hardness than conventional 24 carat Gold.

Alloys powders are available in a wide range of compositions:

- Titanium alloys manufactured using laser melting yield fully dense parts with better mechanical properties than conventionally manufactured components, although thermal treatment is needed to improve densification and relieve stresses in the part [39, 40].

- Nickel-based alloys suffer high cracking susceptibility, which can be improved with stress relieving heat treatment and hot isostatic pressing. Components obtained using laser melting of Nickel-based alloys powders are characterized by better mechanical properties than wrought material [17].

- Iron alloys (steels) usually exhibit balling phenomena (consisting of nonlinear solidification and consequent poor adhesion between subsequent layers) due to the presence of Chromium as alloying element (very active to Oxygen). Therefore deoxidizers need to be used to reduce balling and laser re-melting is performed to improve densification and mechanical properties of the components [17, 41, 42].

- Aluminum alloys require high laser power to be processed effectively (to achieve sufficiently large melt pool creation and oxide film disruption [43]) due to high reflectivity/thermal conductivity of Aluminum and its activity to Oxygen [44, 45]. Moreover, preheating of the powder bed is used to improve dimensional accuracy and to reduce residual stresses together with post-processing heat treatment which is performed to improve mechanical properties. Residual stresses are reduced also re-scanning the processed layer without depositing new powder [46]. The necessity of high laser power and slow scan speeds increase production cost of components manufactured by laser melting of these powders. However, productivity can be improved introducing high power SLM that enables higher scan speeds [45].

- Cobalt-Chromium alloy components produced by laser melting exhibit better mechanical properties than conventionally manufactured components. Furthermore, dense or porous products can be obtained based on the laser energy density adopted during the process. In addition, laser melted components have a better oxide interface for porcelain coatings application.

- Magnesium alloys fabricated by laser melting have mechanical properties which are comparable to those of cast components [39].

Today, the following materials are available from *EOS* [6]: Aluminum alloy AlSi10Mg, Cobalt-Chromium alloys MP1 and SP2, maraging steel MS1, stainless steel GP1 and PH1, Nickel alloys IN625, IN718 and HX, Titanium alloys Ti64 and Ti64ELI. Similar powders are also available from *SLM Technology* [47], *LPW Technology* [48], *Sandvik-Osprey* [49] and other metal powder manufacturers.

7.4 Powders for laser metal deposition

Metals with good weldability and stable in a molten pool are suitable for laser metal deposition [2]. The process can be carried out with blended elemental power to obtain in-situ alloying (yielding custom composition components) or with prealloyed powders [17]. With highly optimized parameters it is also possible to obtain directionally solidified components [50].

Post-processing (hot isostatic pressing or heat treatment) is often carried out after DED manufacturing to improve ductility and reduce crack susceptibility of the material [51].

Today, a wide range of metal powders is available for LENS [52]: Titanium (commercially pure and alloys), Nickel-based alloys, Tool steels, Stainless steels, Cobalt alloys, Aluminum alloys, Copper alloys. These materials are also available from *Sandvik-Osprey* [49], *LPW Technology* [48], and other metal powder manufacturers.

7.5 Limitations and future development

The main limitations and future development needs in the field of metal powders for AM are:

- Metal powders are expensive, research should be focused on methods to reduce their cost [4].
- Full density components need highly optimized process parameters, which are specific of each material [17]. A material processing database and availability of standards would increase reliability and promote industrial applications. Note that the actual trend is opposite: machine manufacturers usually sell metal powders and their optimal processing parameters together with the machine.
- Dimensional accuracy and surface quality are largely inferior to those of traditionally manufactured components. Secondary laser irradiation without deposition of new powder layer and preheating of powder bed can reduce residual stresses and increase dimensional accuracy, but further research is necessary [53].
- Need of high power laser processing for high reflectivity powders, like Aluminum [44].
- Limited set of metals and alloys available compared to conventional manufacturing [4]. Continuous expansion is needed.

Chapter 8

Properties of metal 3D-printed parts

In this chapter, properties such as density, microstructure, mechanical characteristics, residual stresses and surface finish of the metal parts fabricated by the use of AM technologies are described. For each of them, the dependence on process parameters and the post-production treatments commonly used for its improvement are discussed.

AM allows the production of mechanical parts with an extreme degree of complexity, leading to supposedly-impossible geometries and giving engineers and designers the possibility to emphasize on design or functional optimization, rather than machinability. However, such potential for design refinements strengthens the need for ensuring that this innovative technology leads to properties at least similar to those obtained with traditional manufacturing techniques (casting, forging, milling, etc.).

Even though powder-bed based AM may be the unique process able to print controlled-porosity components (filter elements, fluid permeable components, etc.) [54], most developments in terms of process and powders quality have been focused on getting denser parts, in order to maximize material properties and minimize defects generation (including micro-porosity and lack of fusion between neighboring layers) [55].

In order to produce parts with higher density in combination with low surface roughness, it is necessary to optimize, for a specific material, those parameters that are most influencing on the process.

These latter can be divided into four groups:

- material-specific parameters (grain shape, size, distribution, flowability, etc.);
- laser parameters (laser beam power, spot size, focal point, etc.);
- scan parameters (scan velocity, hatch distance, etc.);
- environmental parameters (protective gas atmosphere, ambient temperature, O_2 level).

As shown in Fig. 8.1, such parameters strongly influence the properties of the manufactured parts.

8.1 Density

In general terms, it is proven that densities reachable with laser AM technologies are similar or better than those attained with metal injection molding or casting. In fact, parts manufactured by the use of

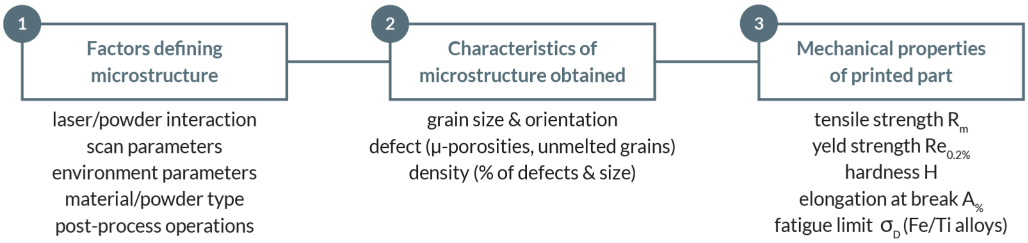


Figure 8.1: Interdependence of AM process parameters, mechanical properties and microstructural characteristics of the manufactured parts [55].

such techniques reveal a density higher than 99.5% and defects usually smaller than 50 μm (<100 μm for IN718) [55]. While a residual porosity cannot be avoided in AM powder-bed based processes, parts that are greater than 99% dense usually require no further sintering or other infiltration process.

It is noteworthy that material's heterogeneity, thus porosity, has a very detrimental influence on fatigue resistance, since it is more likely for a crack to initiate at pores close to the part surface, subsequently propagating while the component undergoes stresses whose amplitude and direction are variable over time. More moderately, other mechanical properties, such as yield strength, ductility and corrosion resistance are also sensible to density.

Powder quality has a significant impact on the ability to produce components that consistently meet stringent specifications. The powder layer density should be as high as possible in order to produce dense parts with high scan velocities and therefore with high productivity [55]. The density of a powder layer is particularly dependent on the particle shapes and size distributions.

Particle shape influences porosity because a greater deviation from spherical shape leads to a lower density, thus more porosity. Moreover, particle size defines how easily the material melts and the size of the resulting pores. A fine powder granulation generally leads to better densities and surface qualities than a coarser material.

Anyways, it is important to qualify a particle size distribution against the background of the layer thickness selected. In fact, in all cases, the "effective" (tapped) powder layer thickness should be relatively higher than the diameter of most of the powder particles, allowing these latter to be deposited within it. A sufficient amount of fine particles is also necessary to fill the voids between coarser grains. However, should the amount of fine particles (about 5 μm or less) be too high, their tendency to form low-density agglomerates (owed to electrostatic forces) eliminates their positive effects of filling up voids and thus it becomes difficult to create appropriate, homogeneous powder layers with a high density [55].

Although it is possible to get high-density parts from different types of powders, process parameters must be adjusted accordingly, thus affecting the build rate. Indeed, when the laser is scanning the powder layer surface, a certain degree of re-melting is inevitable within the last few deposed layers. Thus, if correctly controlled, this phenomenon can help increase the density of the part by removing aligned porosity and some irregularities.

The extent of re-melting depends on the laser power density, the scan speed and the heat evacuation rate of the partly-built component. For a given power and heat extraction rate, while highest speeds result in insufficient melting, the metal density decreases at lowest speeds due to voids created when the laser enters the so-called "keyhole mode" and drills into the layer. Moreover, a thin powder layer will ensure proper inter-layer bonding and a higher density, but it will decrease productivity [56].

Hot Isostatic Pressing (HIP) is a post-manufacturing process commonly used to reduce the porosity of metal parts, providing improvements in their mechanical properties and fatigue resistance. Components are subjected to the simultaneous application of heat and high pressure in an inert gas medium that allows the collapse of voids and porosity by creep mechanisms, plastic deformation, and diffusion, bonding the void surfaces together with minimum distortion. Materials that commonly undergo this densification treatment are high speed steels, stainless steels, Titanium alloys and Aluminum alloys [57, 58].

8.2 Microstructure

In laser-based AM the high energy interaction causes superfast heating and melting of the material, followed by a rapid solidification. The high heating and cooling rates ($10^3 - 10^8 K/s$) at the solid-liquid interface and conduction of heat through the substrate, whose thermal conductivity is higher than that of the metal powders, cause quenching of the material with consequent fine non-equilibrium microstructure, as the time scale of the process is not sufficient for grain growth [59, 17].

The solidification process is the result of two competitive actions: the non-equilibrium solidification influenced by surface tension gradients, resulting from chemical concentration and thermal gradients in the melt pool, and the localized directional growth, due to the kinetic constraint of crystal growth in the direction of maximum heat flow. As a result the material is characterized by a variety of crystal orientations and a consequent anisotropy [17].

As a result of the extremely high cooling rates several effects are possible: the suppression of diffusion-controlled solid state transformations, the formation of supersaturated solutions and non-equilibrium structures, the solidification of extremely fine and refined microstructures characterized by little segregation, and the precipitation of very fine second phase particles [60, 59].

The microstructure is not constant along the height of the component. Microstructural differences, both in grain size and structure, are present between the top and the bottom of laser additively manufactured parts. Grain coarsening in the bottom layers is caused by re-melting which occurs during the addition of the top layers [59] and by long term thermal accumulation. As a result of the different thermal histories experienced by the different parts of the component variation of the microstructure occurs along the height direction [17].

Process parameters exhibit a large influence on microstructural features, through the control of the heating and cooling phases [17]. The laser energy density, a parameter comprising laser power, scan speed, and hatch distance, can be used to control solidification and the resulting microstructure [61]. Moreover, the higher is the scan speed and the lower is the grain size, due to the shorter time spent at high temperature which is available for grain growth [62].

However, variation of the processing parameters to control the microstructure can occur only within a limited region, due to the need of highly optimized parameters that lead to fully dense components. To overcome such issues the microstructure can be controlled using electromagnetic vibrations [63] or applying post-processing heat treatments to the component [64].

8.3 Mechanical properties

Parts resulting from AM processes generally need to be heat-treated in order to achieve optimal mechanical properties. These latter obviously depend on the type of material considered, but also on the part density, and how the microstructure forms.

From a macroscopic standpoint, ultimate tensile strength and elongation generally increase with the final density; anyways, the effect is different for each powder. Pore size has a significant influence on

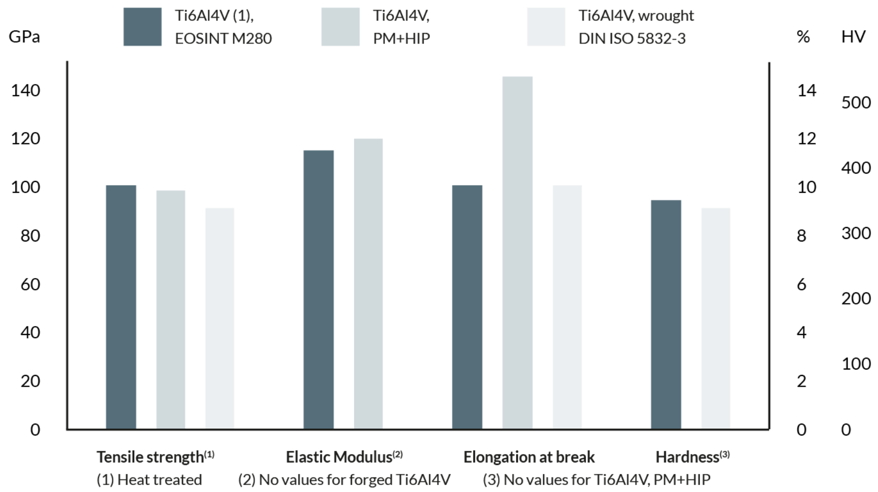


Figure 8.2: Mechanical property comparison for the Ti6Al4V alloy [65].

mechanical properties, since pores can be regarded as defects that reduce the effective cross-section and, when the part is under stress, coalesce, quickly growing in size and therefore leading this latter to rupture.

Short exposure period to the laser irradiation and high cooling rate give rise to printed components with very fine grains, which imply mechanical and physical properties as good as or better than those of comparable wrought or cast materials. A slight increase in strength and decrease in ductility is usually expected because of such refined grains, but this strongly depends on post heat treatment and test direction [55]. This is confirmed by Fig. 8.2, which shows some typical mechanical properties of the Titanium alloy Ti6Al4V used for medical implants.

A good first indication of resistance to deformation is obtained through hardness measurement. Afterwards, tensile tests are recommended on normalized samples to get precise properties such as ultimate tensile strength and yield strength.

Hardness (thus ultimate tensile strength) achieved with AM is usually higher than that of conventionally produced parts due to the natural aging phenomenon that occurs throughout the melting and re-melting of every layer [55]. Depending on the adopted material, a precipitation hardening heat treatment can increase the ultimate tensile strength. While not always, this process often implies a trade-off, at the expense of ductility.

A certain degree of anisotropy in mechanical properties may be noticed in parts manufactured by the use of AM technologies, caused by the layer-by-layer approach. In fact, the tensile strength measured in the build direction is usually slightly lower than in the x-y plane [66]. Anisotropy can be mitigated either before build with a proper laser scanning strategy, either after by an appropriate thermal treatment. Compared with conventional scanning strategies (layers with unidirectional vectors or cross-ply pattern), a rotation from a layer to another leads to better overlapping and less anisotropic properties [55].

Since porosity significantly affects material ductility and hardness, AM processes like SLS/SLM also allow the creation of multi-property components. In fact, by appropriately setting the process parameters (laser power, scan speed, hatch distance, powder layer thickness, etc.), it is possible to control the pore size and thence to design a material according to the required mechanical behavior of the produced part [67].

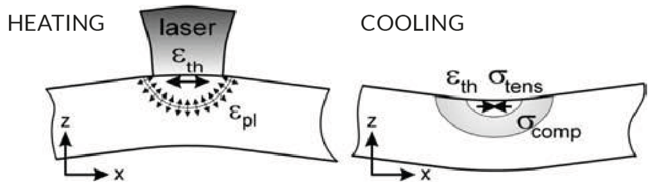


Figure 8.3: Residual stress build-up by the TGM [68].

8.4 Residual stresses

In components manufactured by laser-based AM large residual stresses can be found due to the considerable temperature gradients experienced by the material during processing [68, 17, 60]. Conversely, electron beam melting processed components are free from residual stresses [69, 60].

Residual stress accumulation in the component is undesired as it leads to stress cracking, interlayer debonding and detachment of the component from the baseplate, in addition to hampering dimensional size and shape accuracy with deformations [70, 17].

As shown in Fig. 8.3, residual stress build-up in the component occurs through two mechanisms: the Thermal Gradient Mechanism (TGM) and cool-down phase in molten top layers. The former one consists of the top layer of the component being plastically compressed (due to its thermal expansion hindered by underlying layers and the lowering of the yield strength caused by high temperature) and its consequent shrinkage upon cooling. The latter mechanism consists of shrinkage of the molten layers upon cooling which is prevented by underlying layers, causing a state of tension in the top and a compressive state below [68].

The residual stress profile in SLS or SLM manufactured components is characterized by two zones of large tensile stress at the top and bottom of the part and a zone of compressive stress in between [68, 17]. For DMD processed components the residual stress profile is different: compressive stresses are present in the last deposited region, while previously deposited regions are stress relieved by the thermal cycles induced by the deposition of the following layers [17].

The main parameters influencing residual stresses accumulation are: the height of the component, material properties, scanning strategy and processing parameters. The two most important material properties with respect to residual stresses are the modulus and the coefficient of thermal expansion. The higher they are and the larger the residual stresses built in the part will be [17]. Material with high yield strength will accumulate larger residual stresses than material with lower strength [68]. The laser scanning strategy has a large influence on residual stresses build-up as the stresses accumulated perpendicular to the scanning direction are larger than the stresses found along it [68, 17]. Furthermore, the higher is the number of layers deposited, the larger the accumulated stresses will be [17].

To control and reduce residual stresses in laser-based additively manufactured components several approaches are possible: finite element analysis to predict the material behavior and optimize scanning parameters and processing conditions [70], heating the substrate [68, 17, 60], and stress relieving heat treatment performed either with the laser [68] or by post-processing [60].

8.5 Surface finish

The high quality of metal products produced using AM techniques enables the use of many metal-machining finishes to meet the requirements of surface quality and geometry. In fact, after their production, parts that have to mate with other components can be milled, turned, drilled, etc. in order to make them reach the required dimensional and geometric tolerances [65].

Surface roughness plays an important role in determining how a real part interacts with its environment. Rough surfaces usually wear more quickly and have higher friction coefficients than smooth surfaces; they may also promote adhesion of the part to the others it mates with [71]. Moreover, as fatigue cracks initiate predominantly at the free surface of a material, the condition of the surface can be assumed critical with regards to high-cycle fatigue strength [72].

Since the usual surface roughness values for metal 3D-printed parts range between 5 µm and 20 µm (Ra in x-y direction), a series of post-processing steps is usually needed to improve this feature. The most common techniques are:

- **Abrasive blasting**: is the operation of forcibly propelling a high-pressure stream of abrasive material against a surface in order to smooth it. A pressurized fluid, typically air or water, is used to propel the blasting material. Several variants of the process are bead blasting, sand blasting, wet blasting, and shot blasting [73].

- **Metal polishing**: allows to achieve the full range of surface finishes, including the mirror-like one. Polishing, which can be obtained via manual, mechanical or electrochemical techniques, is often required prior to other surface treatments to prevent corrosion, surface contamination, and not just simply to enhance the aesthetic appearance of parts [73].

- **Electro polishing**: is an electrochemical treatment that significantly improves the surface finish of metal parts. Its first objective is to minimize micro roughness, thus reducing the risk of dirt or product residues adhering and improving the cleanability of surfaces. However, electro polishing can also be used for deburring, brightening and passivating, particularly for surfaces exposed to abrasive media. Since this process involves no mechanical, thermal or chemical impact, small and mechanically fragile parts can also be treated [65].

- **Shot-peening**: is used to improve the mechanical and tactile properties of the surface of metal parts. This treatment implies small balls to impact on the part, in order to induce compressive residual stress slightly below the surface and minimize surface roughness simultaneously. The subsurface compressive residual stress field delays crack initiation and thus postpones crack propagation [65].

- **Femtosecond laser machining**: is a recently introduced microprocessing technique that makes advantage of the ultrafast deposition of optical energy into the material. By using laser pulses with sub-picosecond duration, the zones of the workpiece affected by heat can be significantly reduced compared to longer pulses. Therefore, this process is able of machining several materials, even heat-sensitive ones, with sub-micron precision, smoothing their surface without imparting any thermal influence into the underneath sub-layers [74, 75].

Chapter 9

Software

AM technologies would not exist without computers and software; moreover, their evolution is strictly linked to the future development of programs that will have to better support the entire design process. In this chapter, the role of software in each step of the AM process is described, focusing on the limitations of present software and its future challenges.

The real potential of AM technologies is the possibility to build any geometry that can be virtually modeled with a 3D CAD software, its only limit is human's ability to imagine and design new shapes and structures.

The AM process always from a 3D virtual model, generated by using any three-dimensional CAD system. The only information required for an AM machine is the external geometry definition described by the STL file format and no history about how the part was modeled is needed in order to built the part. For this reason every generic 3D CAD modeling software, no matter what the typology is, has the ability to output to an AM machine.

Once this latter has been properly set up, the modeled part can be printed directly from the STL file without any process planning. Although this is not in reality as simple as it first sounds, AM technology significantly simplifies the process of producing complex 3D parts directly from CAD data [2].

9.1 Software in the AM process

9.1.1 Conceptualization and Computer-Aided Engineering

The very first phase in any design project is the conceptualization of the final output through rough sketches, technical drawings etc. Once the concept idea is completed, the second phase consists in generating a set of 3D source data, either through 3D CAD modeling or 3D data acquisition.

3D CAD modeling is the process of developing a mathematical representation of any three-dimensional surface of a part with specialized software. Three different 3D-modeling methods exist:

- by meshes (subdivision surface, voxels);
- by surfaces;
- by solids (feature tree).

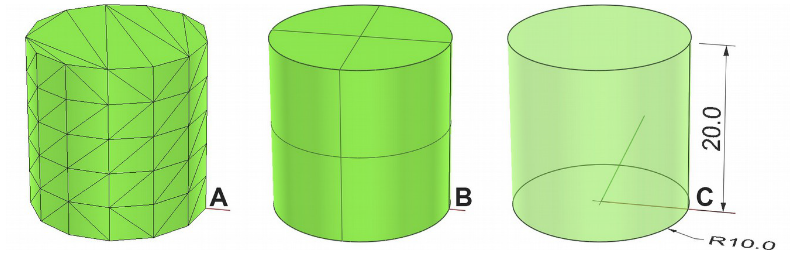


Figure 9.1: Modelization approaches currently existing: A) by meshes B) by surfaces C) by solids.

Every approach has its own advantages and limitations and the choice of which one to use depends on the 3D output required by the project. In Fig. 9.1 there is a clear example of how much is different the approach of every modeling system in order to obtain the same geometric entity like a cylinder.

3D data acquisition is the process of generating 3D models from sensor data starting from a physical object like a hand-made model or sculpture [76]. This data is usually acquired in a "point cloud" form: an unconnected set of points representing the part surfaces. Once these points are connected, the external geometry is created. However, there is often the need of few interventions, like filling holes or not-acquired areas of the part and smoothing in order to create a fully enclosed solid 3D model adapt for printing.

This technology process is known as Reverse Engineering (RE), and software like *Geomagic Design X* can perform such operations on the different scanned part. Objects are normally scanned using a laser-scanning or a touch-probe technology; then, thanks to AM, the scanned parts can be easily reproduced.

Mesh-modeling system

This method approximates the surfaces of a part with a polygonal mesh. Each polygon is planar because is created from the connection of vertices in a 3D space by straight-line segments.

It is a very effective system for unusual designs and shapes rather than basic geometric forms. Since AM has provide a great chance for freedom of expression in terms of shapes, this modeling system is becoming popular among artists and sculptors. As a matter of facts, a subcategory of the mesh-modeling system is the so-called "digital sculpting", that offers software tools to push, pull, smooth, grab, pinch or otherwise manipulate a digital object as if it were made of a real-life substance such as clay. This provides a mechanism for direct interaction between the designers and the modeling material, much like how a sculptor interacts with real clay.

As consumers become more demanding and discerning, CAD tools for non engineers like designers, sculptors and even members of the general public are likely to become more commonplace [2]. Interaction with digital sculpting tools can vary from the standard computer mouse to a digital pen tablet that provides pressure sensitivity adding functionality for most sculpting tools such as *Freeform*, *Mudbox*, *Sculptris*, and *ZBrush*.

Surface-modeling system

This system consists in representing the model as surfaces boundary of the part, not its volume, like an infinitesimally thin eggshell [2].

The main problem with such a representation is to create fully enclosed solid 3D models because they would often appear to the casual observer to be enclosed but in fact were not. An "open" model could result in unpredictable output from AM machines, with different AM technologies treating gaps

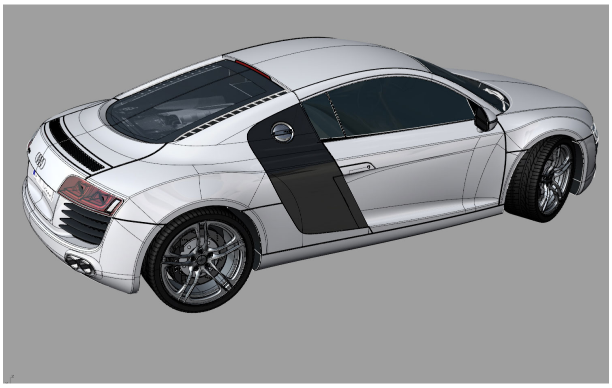


Figure 9.2: Modelization of a car body [77].

in different ways. However nowadays, surface-modeling systems present very few problems with surface discontinuities, with extensive checking and correction software built in.

This modeling system is generally used to describe complex and more organic shapes like the car body shown in Fig. 9.2. Popular examples of software belonging this category are *Rhinoceros* and *Autodesk Alias*.

Solid-modeling system

Parametric solid-modeling CAD systems are generally built on the principle that models are constructed from basic geometry, described by simple features, that are then combined in order to obtain more complex geometries. For instance, the "C"-labeled cylinder of Fig. 9.1 is described by a parametric software like a combination of a specific radius and height.

Typically these kinds of software, such as *PTC Creo*, *CATIA*, and *SolidWorks*, are very good for modeling engineered parts and work on mechanical product development. The strong point is their feature-based modeling approach that enables fast design of parts with many types of typical shape elements and the assembly modeling capabilities that provide means for automatically positioning parts within assemblies and for enforcing assembly relationships when part sizes are changed. In fact, since the part construction history is maintained as a sequence of features, it is simple to quickly edit any dimension of a model, thus generating a new one in a very short time.

CAD evaluation: advantages and limitations

3D CAD is an extremely valuable resource for product design and development for several reasons. First of all, if it is possible to keep the design in a virtual format for most of the product development cycle, any change could be performed easily and cheaply on the CAD data rather than on the physical product.

Another important aspect is that CAD is linked to other Computer-Aided Engineering (CAE) software packages, using techniques such as FEM to calculate the mechanical properties of a design and to determine how well will perform under certain conditions.

Finally, in a software-based design development, AM can be used as an helpful tool to visualize and perform tests on a part thanks to the good "dialog" between the output of 3D CAD software and the required files for AM machines [2].

However, current CAD software packages also have several limitations that prevent an ideal use and integration with AM technologies. Since parametric solid-modeling CAD systems were mainly designed

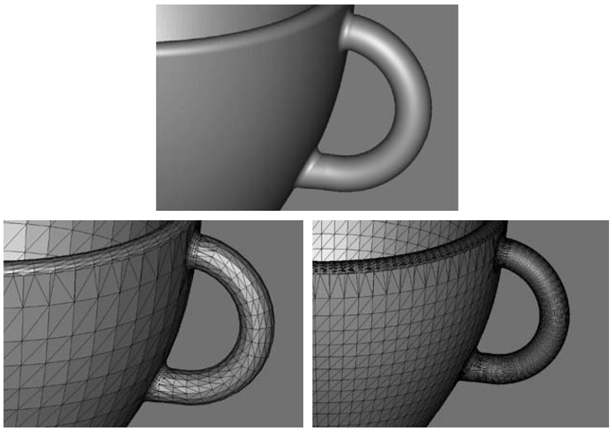


Figure 9.3: Two examples of triangular meshes with different resolutions [2].

for traditional manufacturing process, in some applications they represent a bottleneck in creating novel shapes and structures, exploring the design freedoms of AM, describing the physical properties of the desired part, and specifying material compositions.

These representational problems slow the adoption of AM technologies for use in production manufacture. For these reasons, there is the urgent need of new design systems with interfaces that tend to be more user-friendly, especially for the non-expert designer and more specifically based on the unique potentialities of AM technologies [2].

9.1.2 Conversion to STL file format

The STL (Standard Triangulation Language) file format is derived from the word STereoLithography, which was the first commercial AM process. The basic principle consists in approximating the 3D model external closed surface with several triangular polygons.

The reason to use this format for AM is due to the univocal definition of the 3D model. Indeed, as a matter of facts, each triangular facet is created by the linear connection of three vertices, described by a coordinate system in a 3D space (X,Y,Z) and a normal vector of unitary length to define the upper face of the polygon. In other words, each triangle can be described as an ordinate list of twelve numbers in an ASCII file [2].

It is important to highlight that this file format holds no dimensions, so it becomes fundamental to know the original unit of the CAD data (mm, inches).

In order to output an STL file from a 3D CAD model for an AM machine, two factors are crucial. The first one is the knowledge of how the model has been created and what kind of modeling system has been used, which allows to be sure that it is an error-free fully enclosed model, capable of generating a valid STL file.

Secondly, it is important to know the layer resolution of the AM process (the thickness of a single layer). For instance, if this latter is around 0.1 mm, then a triangle offset (the maximum distance between a triangular planar surface of the STL file and the surface it is supposed to represent) of 0.05 mm will give an acceptable output. As shown in Fig. 9.3, the triangle offset depends on the triangles' size and influences the resolution of the model.

9.1.3 Transfer to AM machine and STL file manipulation

Once the STL file has been exported, it can be transferred to the AM machine to build the part straight away. This is the ideal sequence of actions, but most of the time it is necessary to perform a few operations on the file.

STL manipulation tools

The first step is to verify that the file is fully enclosed, because eventual errors may prevent the part from being built correctly during the process. AM system software normally have visualization tools that allow the user to view and partially manipulate the part.

Nevertheless, sometimes it might be necessary to purchase additional third party software, like *Magics* and 3-matic systems from *Materialise* [78] to perform more specific actions, such as:

- incorporating support structures;
- repositioning, scaling the part or even change the orientation to allow building more than one part at time;
- adding in features like serial numbers and identifying marks onto the parts;
- remeshing STL files that may have been created using RE software or other non-CAD based systems;
- segmenting large models or combining multiple STL files into a single model data set.

Support creation

Supports are normally loose-woven lattice patterns of material placed underneath the areas of the part that need to be supported. Such lattice structures may be created out of simple square patterns, but also through something more complex like hexagonal or even fractal meshes [2].

The support creation phase is normally expected to be automatically carried out by the AM machine built-in software; 3D supports are converted into STL models and are then incorporated into the slicing process.

It is always a good idea, especially for metal part, trying to minimize the amount of supports because wherever they meet the part there will be small marks. Less supports means more accurate part, less waste of material and less time for post-process finishing. Furthermore, parts that require supports may also require planning for their removal because sometimes they may be located in difficult to reach regions within the part.

Slicing

Every AM system is able to read an STL file and to extract the single profile of each layer. A nominal X-Y plane, moving along the Z axis, works as a cutting plane for any triangle intersecting it and creating by this way the resultant slice profile for each layer [2].

A crucial aspect to consider before slicing a 3D model, is the orientation of the part inside the AM machine. For instance, a cylinder built on its side or on its end will produce two completely different results with different part accuracy. Therefore, each model has to be evaluated for its geometry and main features in order to obtain the best possible result in the shortest time.

In fact, building-time increase for the following reasons, which have to be taken into consideration when deciding the orientation of an additively manufactured part:

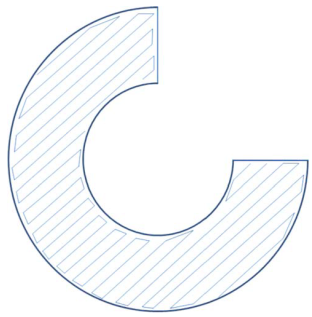


Figure 9.4: Example of layer pattern [2].

- volume of support structures (certain orientation will generate more supports);
- extension of the part along the Z axis.

9.1.4 Machine setup

The next step is to properly set up the AM machine process parameters like material constraints, energy source, layer thickness, timings, etc. According to the variety of materials that an AM machine can work with, the number of setup options increases proportionally; this is because each material has its specific parameters to obtain quality results. However, most systems have default settings to speed up this setup process and to prevent mistakes that may occur due to incorrect parameters.

Trajectories generation

During this phase, building trajectories for each layer are elaborated automatically by the built-in AM machine software. This is done using vectors generated by a patterning strategy called "patterned vector scanning". For a particular layer, a pattern is determined by choosing a specific angle for the vectors to travel. The fill is then a zigzag pattern along the direction defined by this angle. As shown in Fig. 9.4, once a zigzag has reached an end there may be a need for further zigzag fills to complete a layer.

9.1.5 Layered manufacturing

All the stages of the AM process discussed until now are semi-automated. However, human interaction is required, especially to decide the best orientation of the part inside the machine.

The building phase is an automated process which requires only superficial control. To the purpose of assisting the AM process, additional software is usually used for:

- simulating the building process;
- estimating the build-time, so that an effective process planning is possible;
- monitoring the process parameters (temperature of the forming volume, laser powers, etc.).

Chapter 10

Cost analysis and economics

In this chapter, the impact of AM on both scale and scope economies is discussed, together with a broad comparison between conventional manufacturing processes and additive technologies, focusing primarily on traditional drivers, then suggesting new ones that may be taken into consideration when evaluating production costs.

10.1 Manufacturing costs

In the next sections it is shown how in conventional production methods, such as subtractive technologies or injection mold processes, manufacturing costs are higher the more complicated the part shape is and the shorter the production run is. In addition to this, material costs do not typically count for much if compared to the set-up for the production run and the shape of the part. Conversely, with AM, the shape of the part and the length of the production run do not count, while the size of the part is the primary cost driver.

10.1.1 Economies of scale

Economies of scale describe the cost advantage that arises with increased output of a product. This generally happens because of the inverse relationship between the quantity produced and per-unit fixed costs. Although economies of scale often originate with fixed capital (which is lowered per unit of production as design capacity increases), also variable costs per unit may be reduced thanks to the achievement of operational efficiencies and synergies in different enterprise areas. For instance, increasing delivery speed lowers both fixed and working capital costs, and bulk buying of materials through long-term contracts can improve purchasing department performances.

While the benefits of this concept in areas such as production and purchasing are obvious, economies of scale can also impact unexpected areas, like finance. For example, larger companies often show a lower cost of capital than smaller firms because they can borrow at lower interest rates. When evaluating an investment in machinery, using a classical approach, in order to justify such investment, since new technologies require large amounts of capital to develop and deploy, similarly large quantities of product are required to amortize the investment over many individual units of production.

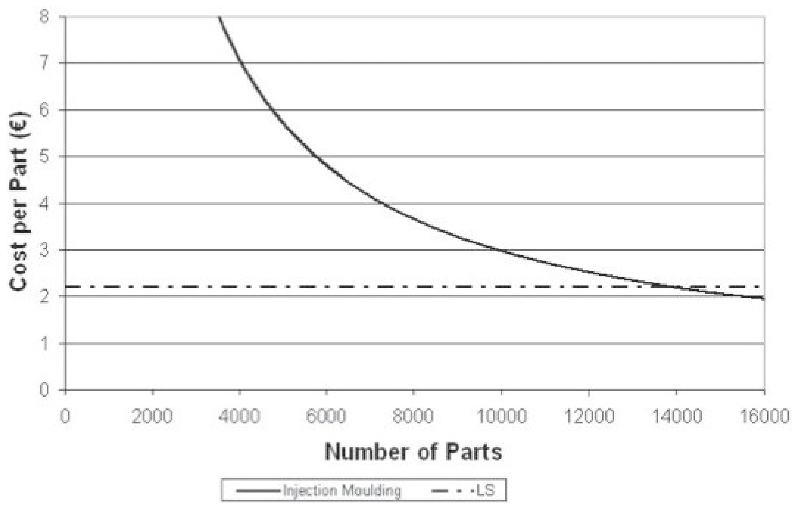


Figure 10.1: Example of break-even analysis comparing SLS with IM [79].

Initial studies on AM production costs showed a flat line, suggesting that marginal costs were independent from production volumes [79]. The authors calculated the cost of a part assuming that the machine was producing only copies of the same part and using a constant production time. Their model was used to calculate a first approximation of break-even analysis of SLS compared to Injection Molding (IM) techniques, in order to find when AM was economically convenient [79].

Fig. 10.1 illustrates the change in average cost for each incremental unit of production for the AM and IM techniques. Break-even between two alternative production approaches occurs where these curves cross. This plot effectively shows that AM used for low-medium batch sizes of production is capable of being highly economical, while traditional methods still prevail for very large volumes.

In-depth studies have showed something different, since a new cost algorithm that attributes costs to the individual part build time has been developed [80]. This research allows to visualize the effect of production volume on the costs for particular parts. As the production volume increases, these effects are manifested as oscillations in the cost curve, which can be attributed to the packing density of the build volume, as shown in Fig. 10.2. In fact, when a build volume is completely full, it is necessary to use a second production bed to manufacture additional part. This results in incremental costs due to the added build time and the further heating and cooling cycles necessary for the second build.

Eventually, economies of scale in AM are a consequence of both the sizes of the part and the forming chamber (big parts take more space, so the additional cost is split among fewer parts) and the efficiency in packing the parts in the build room (also called packing ratio) [80].

Fig. 10.3 compares three versions of the model proposed by Ruffo et al. [80] to the result reached by researchers Hopkinson and Dickens [79] and an IM cost function. This research has quantified and demonstrated that economies of scale are possible with AM production, although not nearly to the same degree as most conventional methods of manufacturing, such as IM. In fact, break-even production volume for AM versus IM changes considerably. This happens because AM eliminates setup costs and significantly reduces the need for tooling, while in IM fixed tooling costs dramatically increase the cost of low production volumes.

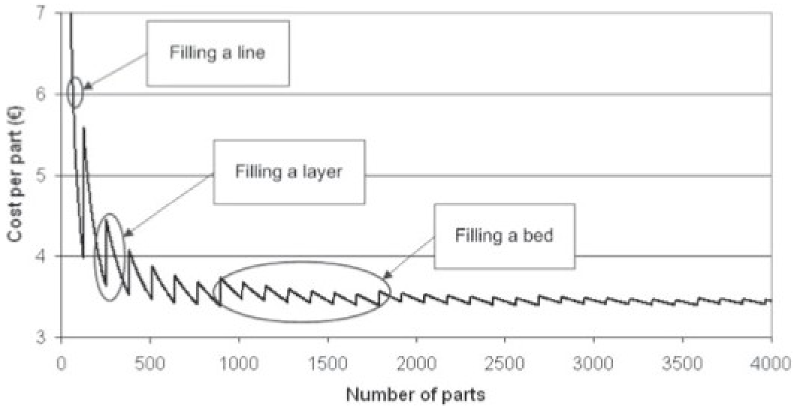


Figure 10.2: Production curve for SLS [80].

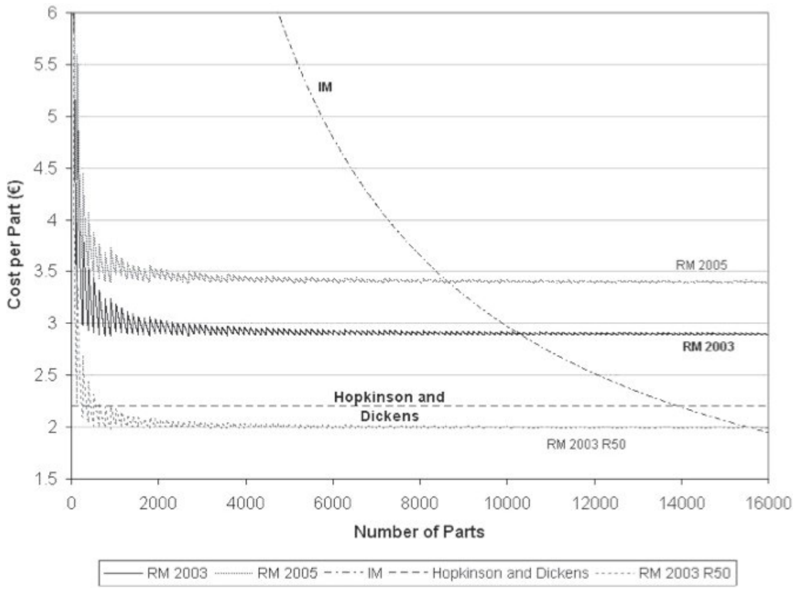


Figure 10.3: Comparison of SLS cost function with IM [80].

10.1.2 Economies of scope

Economies of scope deliver advantage by allowing the production of multiple different end products using the same equipment, materials, and processes; unit cost falls as the number of products that can be made using the same invested capital increases.

AM flexibility decreases the capital required to achieve scope economies. In fact, by using AM, it is possible to realize different product configurations with reduced changeover time and cost (sometimes no changes in tooling are required to make the AM device shift from a part to a completely different one).

10.2 From design for manufacturing to design for function

Traditional production processes often impose design limitations. For instance, the need to be able to remove the manufactured part from a mold creates a limitation for molding methods. Moreover, these latter are then often limited by straight line drilling, causing inefficient cooling systems; in fact, no subtractive manufacturing technique is able to create, for instance, hollow structures [4]. These

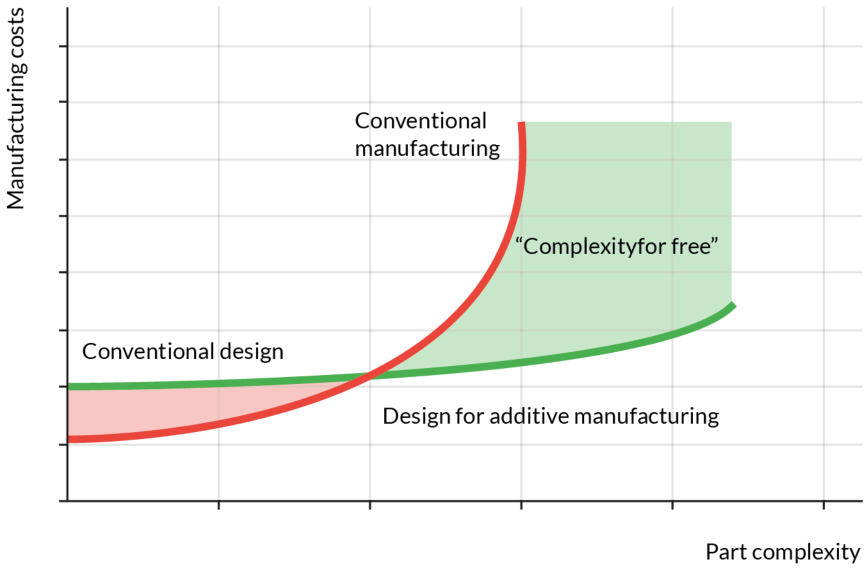


Figure 10.4: "Complexity for free" diagram [83].

limitations can proliferate the number of parts required to produce a component.

As the geometric complexity of a component increases, it can prevent a part from being fabricated as a single piece, while AM multi-functionality design can reduce part count [81]. Using AM, designers have greater design freedom, being free to explore shapes that would otherwise been impossible to produce (or would have been prohibitively expensive). Components can be customized with specific internal geometries, porosities or surfaces, thus allowing the production of extreme lightweight structures. These additional and enhanced capabilities compared to the conventional manufacturing technologies are highly related to costs and the part design.

A popular term to describe the new possibilities enabled by AM is "complexity for free", as shown in Fig. 10.4. In particular, optimized, free-form internal channels and structures can be produced; structural material can be only used where it is needed [82]. It is even possible to build "instant assemblies", that are pre-assembled items with multiple moving parts. In this regard, examples can be taken from the aerospace sector, where *The Boeing Company* has successfully redesigned the environmental control ducting system of the *Boeing F-18* military jet and the *787* commercial airliner, consolidating 10-20 parts into one single piece [4].

In conclusion, not only production volume, but also part size and complexity have to be analyzed to tell if it is worth manufacturing a component with AM. A small and complicated part is more likely to be economically feasible for AM, while a large, simply shaped component is probably not a good candidate for AM. These three aspects together presently represent the criteria that drive a company's decision. However, these rules may change over time, as systems will become faster, larger, and less expensive to purchase and operate.

10.3 AM costs versus traditional process costs

Although traditional techniques are more economically viable in most situations, AM is receiving great attention thanks to the potential benefits it could bring. In the following sub-paragraphs the potential benefits and actual limits of AM, compared to other technologies such as IM and cutting-based machinery/subtractive technologies, are listed according to their area of impact.

Machine and tooling purchase In contrast to IM or die casting, AM process does not involve the use of molds to create different products. Moreover, contrary to other typical manufacturing techniques such as milling, AM does not require expensive tooling, forms, or punches. The main limitation is the actual cost of the machine itself, because the technology is still relatively new, especially for those devices capable of producing end-usable parts [82].

Maintenance and changeover costs Using AM, if different parts of the same material have to be manufactured, little set-up is needed. In fact, for metal processes, the only operation that has to be carried out before the production of the component can start is the creation of support structures. These latter anchor the part to the base plate and reduce the warping caused by thermal stresses during the build. In powder bed processes sometimes the chamber also needs to be pre-heated [4]. However, changeover costs are significantly lower if compared to those of production shifts of conventional processes [82]. On the other hand, maintenance to AM machines is less standardized and, thus, more costly.

Material consumption and purchase Another limit to the widespread utilization of AM lies in material purchase costs. In fact, getting raw material into a usable form constitutes a challenging task for AM, especially when dealing with metal powders, since pulverization processes are relatively new [82].

However, AM technologies can improve material utilization. Using traditional manufacturing techniques, such as die casting or IM, raw parts are formed in a mold and some of the excess material has to be removed afterwards. Additive processes, instead, can handle shapes that eliminate unnecessary mass and create them without such waste.

According to some studies, material waste in metal applications associated with AM is reduced by 40% in comparison to machining and subtractive technologies. In addition to this, 95% - 98% of waste material can be recycled in AM [84]. In fact, subtractive technologies can remove as much as 96% of the raw material when creating a product [85]. For instance, CNC milling machines often have scraps rate as high as 95% in the aerospace industry [4]. In contrast, AM reduces scraps rate to 10%-20% [85].

Another advantage is related to lightening of parts (i.e. manufacturing a product using as little material as possible, still maintaining its structural integrity). As a matter of facts, AM can create highly complex geometrical structures that reduce the amount of consumed material (buy-to-fly ratio). For instance, internal lattice structures provide support only in the areas where the product is under stress [82]. Eventually, less material being used means less time to process the material and faster build times.

Labour costs AM is a capital intensive, automated process, that reduces the need for workers, in particular if a new design of a component cuts some assembly phases. However, more skilled personnel will be needed, having competences to run AM machines [86, 83].

Inventory While manufacturing pre-assembled parts can reduce work-in-process (and thus, improve net working capital), producing on demand allows the reduction of finished goods stocks. For instance, in the aerospace industry it is said that nothing is more expensive than an airliner on the ground, because of the huge amount of spare parts stocks needed [87]. But if AM will be able to produce spare parts when needed, only raw material stocks will be required.

Transportation With AM, manufacturing can be brought back to a local scale reducing transportation costs, eliminating outsourcing need of special parts. Moreover, lightweight parts may be more economical to transport [4, 88].

Energy Many AM processes use significant amounts of electrical energy per unit mass of material processed. For instance, the powder bed fusion process can consume up to 100 times more electrical energy to consolidate 1 kg of Titanium than is needed for the investment casting or CNC machining of the same amount of metal. However, this comparison is misrepresenting, since the energy use of an AM machine should not be directly compared to that of a traditional manufacturing process without taking into account the additional energy required to produce the basic mill forms. These services can include ingot making, rolling, extruding, etc. [4].

Post-processing Post-processing refers to all the activities required after the AM build process to achieve the desired product properties.

First, in PBF processes, loose powder has to be removed from the part (using compressed air or ultrasonic cleaning equipments). In powder-bed laser-based systems, the powder that has not fused during the build process remains in the solid state, while in powder-bed electron-beam-based processes a shot peening operation may be needed, since unused powder usually is in the semi-solid state [4].

After that, metal AM parts are often heat-treated to remove internal stresses or to promote specific metallurgical conditions. It also may be necessary to remove build support structures.

Finally, most metal AM parts need surface finishing to achieve specific roughnesses or to meet the designated dimensional tolerances [89]. This is typically obtained through machining, which can be used both to change the material properties and to improve the surface quality. Grinding and polishing by hand are also possible, but even if these techniques are standard in the prototyping business, they are too costly for most production processes [4].

A particular technique allowing for obtaining mirror-like surface qualities of metal components is the Micro-Machining Process (MMP), developed by *Swiss BinC Industries*, which combines a chemical reaction at the surface of the material with a removal process driven by fluid flow [90]. The MMP process is used for large numbers of identical or similar parts and for high-value parts, since it requires a setup specifically related to the geometric features of the part. These steps introduce extra cost, extend the manufacturing cycle and increase the possibility of process variance [89].

Tab. 10.1 underlines some of the characteristics described above, dividing costs between variable with production and fixed costs.

10.3.1 Drivers indicating suitability of for AM production

A case-study analysis on one part may also include additional variables, such as the production volume, the material cost per part, the mold cost per part, the processing and post-processing cost per part [82].

Materialize, a company specialized in AM software and consultancy, provides at *http://3d-print-barometer.com/configurator.html* a simple tool that helps one to understand how suitable the parts are to be manufactured using AM techniques. The so-called "barometer" takes into account five dimensions:

- part size: the smaller the part is, the better it is for AM productions;
- part complexity: AM manufacturing costs do not increase with the complexity of the part;
- project value (finished good value): since the depreciation of the AM machine has a fundamental impact on costs, it is more probable to have a positive marginality if the product price is high;
- series size (from 1 to 10,000): AM is more indicated for small series;
- visual or functional purpose: it is better to use AM for functional purposes.

	Cost	Hypotesis	Machine Process	Injection Molding	Additive Manufacturing
Machinery	Fixed				+
Tools	Fixed		+		
Mold Costs	Fixed			+	
Change Over	Fixed	*same material	+	+	
Maintainance	Fixed	*prevenience maintenance			+
Surface Quality	Variable			+	+
Post-processing Heat Treatment	Variable				+
Raw Materials Costs	Variable				+
Scaps	Variable		+	+	
WIP	Variable		+	+	
Energy Consumption	Variable			+	+
Personnel	Variable		+	+	
Training Costs	Variable				+

Table 10.1: Cost items summary.

10.3.2 Limits to AM production

The main limitations that present additive technologies have to overcome in order to become a valid alternative to conventional manufacturing processes are: production speed, dimensional accuracy, surface finish, process and product repeatability [91, 89].

While AM allows faster low-volume productions than conventional manufacturing processes, it is considerably slower with higher volumes, because the build rates of today's machines are too low. Indeed, most applications require powder bed-based processes to be four to ten times faster than present ones.

At the current build rate, machine depreciation results in parts of too high cost, except for some very small complex geometries, such as dental implants [89]. Making parts in parallel production, that is filling the building platform area as much as possible, speeds up the process, allowing AM to start competing with conventional manufacturing processes as IM. In fact, the flexibility of additive techniques allows the production of several parts at a time, which can be different from one to another. For this reason, it is possible to define AM as a "parallel process", where different parts can be built contemporaneously [80].

In order for AM to compete with conventional manufacturing processes, not only its productivity, but also the output quality and the process repeatability have to be improved [91]. Highly regulated sectors, such as the aerospace and the biomedical ones, require that new products and processes meet exacting industry standards before they can be introduced. This qualification necessarily involves longer and more rigorous development and implementation cycles, which add to the costs [89].

Consequently, for AM to be accepted as a production method, system manufacturers have also to implement statistical process control and closed-loop feedback subsystems that ensure quality of the products. Without systemic control, AM machines will not develop into true production systems [91].

10.3.3 A lifecycle approach to cost analysis

Although the team did compare AM to traditional manufacturing processes, any cost analysis of 3D-printed parts should avoid a "like-for-like" comparison with existing product designs being manufactured using conventional processes. Instead, a broader analysis should be carried out, including all the value chain activities.

First of all, products should be redesigned keeping the layerwise manufacturing approach in mind, so that they can take advantage of the discussed technological capabilities, such as part consolidation and customization [4, 2]. This latter is a real business opportunity, therefore an improved customer satisfaction, as well as the incremental costs that customers are willing to pay for a customized product, should be quantified [4, 85].

Manufacturers should also consider a redesign of the production process, so that they can take advantage of a reduced inventory and more immediate responses to changes in product mix [4].

Furthermore, AM can reduce product development risks, and responsive production can lower the time to market, especially if one considers that, using traditional manufacturing methods, developing a new product typically requires several weeks in order to produce the necessary tooling before production can even begin, while, with AM, the production can start almost as soon as the CAD development phase is completed [82].

Moreover, thanks to the shortening of supply chains, even logistics costs may be cut.

Lastly, even those costs that are not directly related to production and delivery should be considered, including the ones that manifest in later lifecycle phases, as product maintenance, or automobile/aircraft fuel consumption [2]. For instance, lightweight aircraft parts can lead to huge differences in fuel consumption, and therefore cost. To this purpose, a consortium based in Germany and consisting of *Laser Zentrum Nord GmbH*, the *Institute of Laser and System Technologies* (ILAS) of Hamburg University of Technology, and *Airbus Operations GmbH* has shown that "eliminating 100 kg is said to save an airline 2.5 million USD annually in fuel costs for short haul flights" [82].

Part IV

Design for AM

Chapter 11

Structural optimization

In this chapter, the design process of parts conceived for the production by AM technologies is described. The differences from the traditional design approach and the resulting benefits are stressed. Particular emphasis is given to structural optimization, thanks to which significant improvements in the performance of manufactured parts and AM processes can be achieved.

Design for manufacture and assembly has typically meant that designers should tailor their designs to eliminate manufacturing difficulties and minimize production, assembly and logistics costs. However, AM technologies provide an opportunity to rethink this process, in order to take advantage of the unique capabilities they offer. These latter include [2]:

- shape complexity, in that it is possible to build virtually any shape;
- hierarchical complexity, in that hierarchical multi-scale structures can be designed and fabricated from the microstructure through geometric mesostructure (sizes in the mm range) to the part-scale macrostructure;
- material complexity, in that material can be processed one point, or one layer, at a time;
- functional complexity, in that fully functional assemblies and mechanisms can be directly fabricated.

Due to the layer manufacturing approach, the increased complexity of parts generally does not have much effect on the cost of the process. This provides designers with significantly greater design freedom and enables the built part to be closer to the optimum design than is possible with traditional processes such as casting and machining, which have significant manufacturing constraints that limit the physical realization of the optimal topology. Therefore AM, avoiding the need of a compromise between optimality and ease of manufacture, allows design optimization through the use of advanced FEM-based simulation technologies.

As Fig. 11.1 shows, the typical design approach involves numerous trade-offs (appearance vs. function, cost vs. ease of manufacture, etc.) that imply inevitable changes to the design, which may become prohibitive at a certain stage of the process. Therefore, it is easy to understand how the concept phase plays a fundamental role concerning the overall efficiency of the product development process [92].

Rather than using CAE software to verify proposed designs, the preferable approach, introduced after the advent of AM technologies, consists in using optimization software to suggest a design that is much

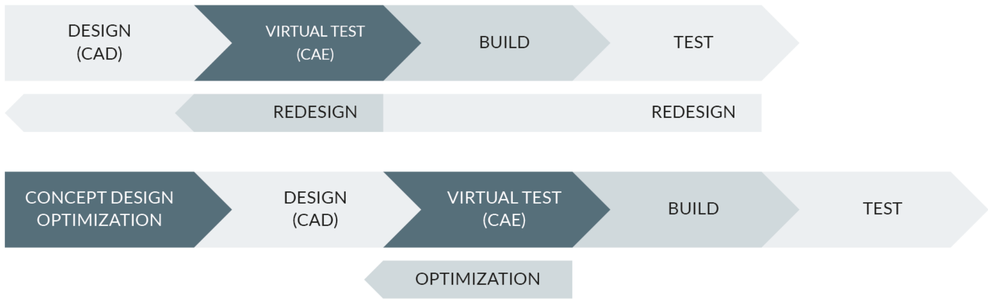


Figure 11.1: Comparison between the typical design approach (on the top) and the recently-introduced one, based on the use of optimization software (on the bottom).

more likely to work. Such a method noticeably changes the way parts are designed, since the traditional verification stage can be approached with a much higher level of confidence and, in many cases, the redesign cycle can eliminated [92]. This replaces time-consuming and costly design iterations and hence reduces design development time and overall cost while improving the performance of the output.

It is important to stress the fact that, like anything with CAE, optimization software is a tool, and it does not have engineering judgment, so the ultimate design decisions lie with the user. Thus, at the end, "extracting" the best design out of many different proposals is also a matter of experience.

Design optimization usually affects the part structure, which is the physical layout that directly controls its properties. By the application of different structures (either at micro, meso or macro scales), parts can be optimized in terms of [93]:

- stiffness and strength properties;
- compliance properties;
- dynamic properties;
- thermal properties;
- visual properties.

11.1 Lightweight part manufacturing

Nowadays, strength and stiffness optimized for weight are the most promising characteristics of AM-made products. Structural optimization in terms of these properties can be achieved by the use of mathematical approaches that optimize material layout within a given design space, for a given set of loads and boundary conditions, such that the resulting layout meets a prescribed set of performance targets [94].

This approach leads to parts that are lighter, stronger, and typically more energy efficient, since keeping the unnecessary material out of the design eliminates the need of its mining, processing or disposal, and this extra weight loss reduces fuel consumption and the energy required to carry this weight [95].

Although it may lead to huge material and energy savings if applied vigorously and throughout all industries, topology optimization currently shows great potential in the automotive and aerospace fields. In fact, tougher fuel economy and emissions standards are driving lightweight design efforts for cars and planes, since even modest weight savings result in huge overall fuel consumption and CO_2 emission savings over a vehicle's lifespan. It is therefore easy to understand why many present companies are prepared to accept the added computational expense at the design stage to improve the optimality of the results [92].

11.2 Topology optimization algorithms

The design of lightweight load-adapted structures is currently aided by structural optimization (in particular topology optimization) software, which numerically determine the part's volume of structural relevance.

Assuming the material's strength and stiffness to be linearly dependent on its density, the optimization algorithm is based on the calculation of an "equivalent density" (treated as a design variable) for each element of the meshed design volume. This variable ranges from 0 to 1, where 1 is equivalent to 100% material, while 0 is equivalent to no material in the element [92].

Given certain load and constraint conditions, the solver seeks to assign elements that have a low stress value a lower equivalent density before analyzing the effect on the remaining structure. In this way, extraneous elements tend towards a density of 0, while the optimum design tends towards 1 [92].

In order to obtain an optimized geometry, the material density of each element should take a value of either 0 or 1, defining the element as being either void or solid, respectively. Unfortunately, being the optimization of a large number of discrete variables computationally prohibitive, an evaluation of the material distribution in terms of continuous variables has to be conducted, with values of density between 0 and 1 representing fictitious material [92].

Therefore, techniques need to be introduced to penalize intermediate densities and to force the final design to be represented by densities of 0 or 1 for each element. A widely used method that allows this is the *Solid Isotropic Material with Penalization* (SIMP) scheme, which makes use of a penalty factor to discriminate between void and solid [96].

11.3 AM constraints

So far, there has been no research on methods for incorporating specific AM constraints into topology optimization algorithms. The only existing applicable method is the minimum member thickness constraint, which can be exploited to guarantee the minimum feature size possible for the AM process.

With the aim of reducing material usage for supports and subsequent post-processing, a maximum overhang constraint would need to be based on the maximum horizontal overhang distance and on the overhang angle. In any case, a maximum thickness constraint has some relevance to this issue, since it results in an increase in the quantity of members. This reduces the horizontal overhang distance between these latter, thereby limiting the amount of support structure required. Nevertheless, it is difficult to know in advance what specific maximum member thickness value to use, then several runs are required to adjust this parameter. It is also unlikely that this constraint completely eliminates the need for any support material as it does not penalize large unsupported cavity edges [94].

For areas of the part that have to mate with other components, or that require very high accuracy, post machining may be necessary. Therefore, in these cases, a machining constraint would be useful to ensure the tooling can attain access to the relevant features of the component.

11.4 The topology optimization design process

The starting point of the process, schematically shown in Fig. 11.2, is the definition of the so-called "design space", that is the volume of the part designable by the optimization software. In order to maintain the functionality of the component while it mates with others, it is necessary to specify the mechanical coupling regions, which have to be excluded from the design space since they must not be altered [92].

With the application of the appropriate displacement constraints and loads, which simulate the prescribed working conditions of the part, the FEM mathematical problem becomes nonsingular and the solver can calculate the optimal material allocation according to the given requirements.

As Fig. 11.2 shows, the result given by this kind of software has to be understood as a design suggestion. Due to the currently only marginal acquaintance of the restrictions inherent to the AM process, alongside the use of conventional lightweight design guidelines, it is essential to incorporate AM-related constraints into the design process. In fact, the manufacturability and profitability of the designed parts can be assured only by taking into account the necessity for support structures, the containment of the anisotropic nature of part strength and the prevention of thermal induced stresses [95].

Based on the results of the interpretation, the remodeling of an appropriate geometry using a 3D CAD modeler is performed. Since current automatic mesh-to-solid conversion tools cannot handle high levels of geometric complexity, this stage usually has to be done manually by the designer by "tracing" the optimization result.

Since STL files are used as the standard geometry file format for AM, it is also common to generate a surface mesh from the optimized topology model and carry out further tasks at the STL level, thus avoiding the cumbersome conversion to a CAD format [94].

In order to verify the fulfillment of the part's requirements, the generated 3D model subsequently has to undergo a more accurate FEM structural analysis, performed under the most unfavorable loading condition. If the chosen design does not meet the required demands, an iterative redesign process takes place.

11.5 Optimized cellular and support structures

Unlike traditional manufacturing technologies, AM offers the possibility to produce lightweight parts by creating regions of intermediate density, using either small-scale cellular structures or multiple material processes [94].

The concept of designed cellular structures such as lattices, honeycombs, etc. (an example of which is given in Fig. 11.3) is motivated by the need for a substantial weight-to-strength ratio improvement over solid wall construction. To this end, the engineered optimization of such structures via automated population of complex geometry leads to consistent results with the alignment of unit cells along force directions. In addition to this, good energy absorption characteristics and good thermal and acoustic insulation properties are shown by these kinds of structures [97, 98].

Since supports usually represent a considerable waste in terms of material, energy and time employed for their construction and removal, a recently introduced approach aims at optimizing these structures and the part built orientation. In order to achieve this, a FEM-based optimization algorithm is applied and pure mathematical 3D implicit functions are used for the design and generation of cellular support structures, so that they provide more robust support where the weight of the part is concentrated, and less support elsewhere [100, 101]. In this way significant savings can be achieved, therefore the sustainability and efficiency of the AM process are improved [100].

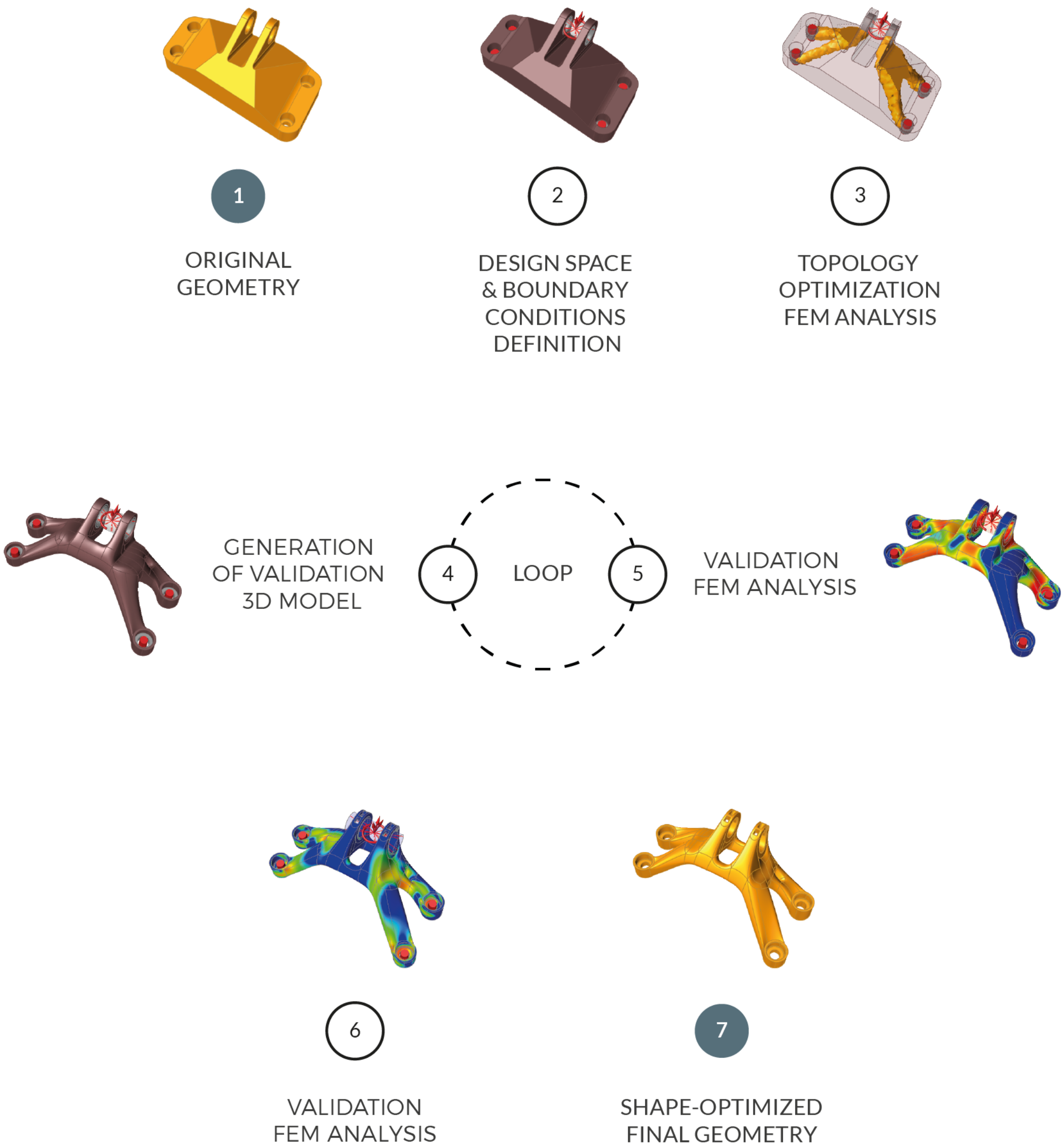


Figure 11.2: Workflow of the topology optimization design process.

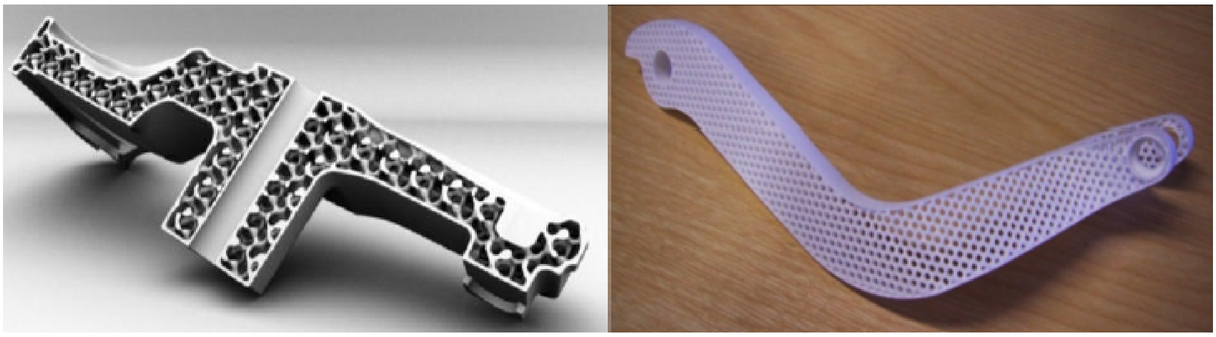


Figure 11.3: Two examples of designed cellular structures [99].

Chapter 12

A case study

In order to point out the benefits obtainable by the use of lightweight parts conceived for the production by AM technologies, a case study is presented in this chapter. The improvements in energy efficiency brought by the component under examination are described and detailed, along with the results of the evaluation of its production costs.

The present case study regards a bracket made of Titanium alloy (Ti6Al4V), which has been optimized for its structural function. This part is a component of the CFM56-7 turbofan aircraft engine made by *CFM International*, which powers the *Boeing 737 Next Generation* series (737-600/-700/-800/-900), a family of short- to medium-range, narrow-body jet airliners produced since 1996 by *The Boeing Company* [102].

The original component, shown in Fig. 12.1, was designed for conventional manufacturing technologies (milling in particular); therefore, as FEM analysis has proven, it was not fully optimized for both performance and weight due to manufacturing constraints. Exploiting the possibility offered by AM to grow practically any shape, the design process described in Sec. 11.4 has been put into practice, using the commercial optimization software *SolidThinking Inspire* by *Altair Engineering* (based on the solver named *OptiStruct* [92]) as an aid for obtaining a topology suggestion.

As a result of few design iterations, a part fully optimized from a strength-to-weight standpoint (shown in Fig. 12.1 as well) has been conceived, capable of still matching the interface dimensions and bearing the given loads without failure. Indeed, as Fig. 12.2 testifies, the minimum static factor of safety, evaluated under the most unfavorable loading condition, is around 1.5. Such lightweight part has proven to be 76.5% lighter than the original one; this extra weight loss obviously implies important benefits in terms of fuel consumption and CO_2 emission savings over the airplane's lifespan.

12.1 Production process description and cost analysis

With the aim of producing a full-scale demonstrator, the optimized part shown in Fig. 12.1 has been physically manufactured in Aluminum alloy (AlSi10Mg) through the SLS process by using the *EOS M 270* machine located at *IIT* of Turin.

After the production, a manufacturing cost analysis has been carried out, based on the data collected by interviewing the technical personnel of *IIT*. The major cost items of the AM process have been found

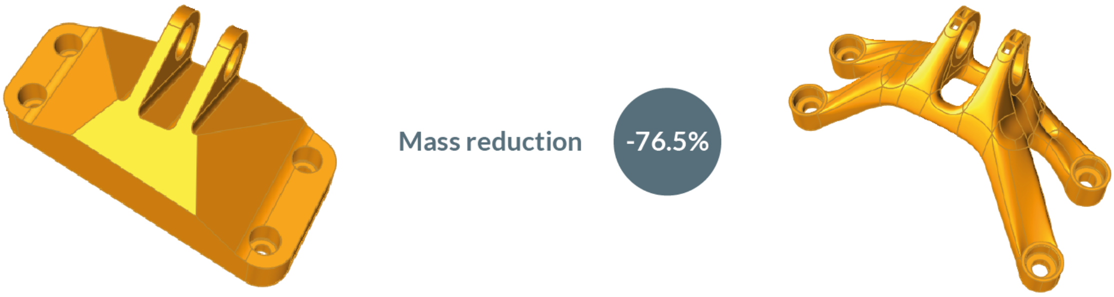


Figure 12.1: The original part object of the present case study (on the left) and its optimized version (on the right).

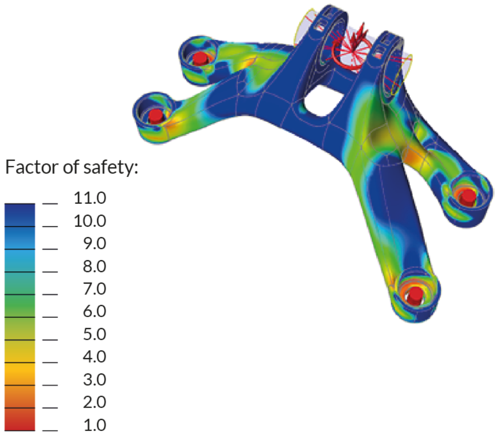


Figure 12.2: Colormap of the optimized part's factor of safety, evaluated under the most unfavorable loading condition.

to be the ones listed and described below; their incidence on the total production cost is represented in Fig. 12.3.

- **STL file and job preparation cost**: in order to guarantee the reliability of the 3D-printing process and the quality of the final part, the triangulation of the part geometry has been analyzed and manually corrected, so that a proper number of triangles (not too high, not too low) approximated the surfaces of the component. Moreover, according to the selected metallic material and the desired quality of the output, the process parameters (195 W of laser power, 800 mm/s of scan speed, and 0.17 mm of hatch distance) have been set, following the machine manufacturer's guidelines.

- **Machine's set-up and depreciation costs**: the AM device has been first loaded with virgin 50 µm metal powder; after the completion of the 3D-printing process, the platform carrying the manufactured part has been pulled out of the machine. The depreciation of this latter has been calculated on the base of the production time of the component.

- **Machine's operating cost (inclusive of electric energy, inert gas and metal powder)**: the layer thickness has been set at 30 µm, therefore the part (170 mm × 100 mm × 60 mm) has taken 19 hours to be manufactured; the forming room's atmosphere has been kept at an average Oxygen concentration of 0.1% thanks to a controlled flow of Argon gas.

- **Support removal cost**: following the stress relief heat treatment, the part has been separated from the building platform by manually removing the metal supports.

- **Post-processing cost**: after the component was pulled out of the AM device, it has undergone a heat treatment with a temperature gradient (ramp up to 300 °C over 2.5 hours, holding at 300 °C for 2 hours, cooling in the oven) defined by the machine manufacturer. Following the removal of supports, the part has been post-processed with the shot-peening technique (with 4 bar peening pressure and 200 µm zirconia spheres), then the mechanical coupling regions have been manually polished.

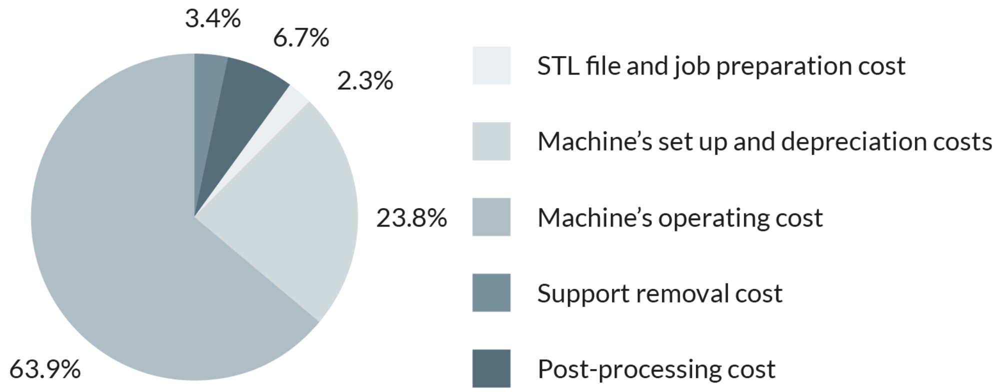


Figure 12.3: Distribution of the AM process cost items relative to the present case study.

12.2 Benefits of extra weight loss

In order to emphasize the improvements in energy efficiency that can be achieved by installing lightweight parts, a study has been carried out on the impact of the weight reduction brought by the above optimized component on the performance of a commercial airplane currently equipped with CFM56-7 engines. The baseline vehicle selected for this kind of evaluation is the *Boeing 737-800 (Next-Generation)*, nowadays the most popular airliner in the world, carrying more than 1.5 million passengers every day [103]. Since the original version of the engine bracket under examination weights about 2.090 g, while the optimized one is only 490 g (-76.5% in weight), the redesign process has resulted in a 3,200-g reduction in the weight of the twin-engine propulsion system of this aircraft.

The theoretical model that has been used for estimating the contribution of each sub-assembly of the airplane to its total weight and moments of inertia is the one developed by E. Torenbeek [104], which has been applied on the aforementioned baseline vehicle assuming that it carries an average of 180 passengers per flight. Since a reduction in the weight at takeoff implies a smaller amount of fuel stored in the aircraft's tanks, the problem has required an iterative solution process.

In the case of a flight of 4,000 nautical miles (very close to the airplane's maximum range with the above payload), the *Torenbeek model* has returned a value of 3.2 litres of fuel saved per flight. Since the airliner chosen as baseline usually operates on an average of 10 flight hours per day, this results in a saving of about 27,160 litres of fuel over its average 20-year lifespan, which implies both a reduction of about 21,000 USD in the airlines' operating costs and a decrease of almost 70 tons in CO_2 emission over such period of time. It is easy to understand how significant the savings in terms of fuel consumption and greenhouse gas emission might be if design for AM was to be applied to components that are heavier than the present one.

Part V

Solution

Chapter 13

The future of metal AM

In this chapter, the solution process that has led to a possible concept of the AM "machine of the future" is described. Starting from the examination of the technological trade-offs intrinsic to the SoA of metal AM, the features necessary to the team's concept are outlined. This latter is then presented and compared to other possible solutions given the present trends in the sector. Finally, an evaluation of the concept feasibility is carried out with both a top-down and a bottom-up approach, which respectively lead to the present value of cash flow delta and break even point.

13.1 Technological trade-offs

The analysis of the present SoA of the metal laser AM technology has allowed the team to identify the following trade-offs, which have to be put into practice by end users when dealing with the design and fabrication of an additively manufactured part.

Process parameters The main parameters of the metal AM process, deeply discussed in Chap. 6, characterize the laser beam, the scanning head and the working environment. End users usually choose their values in the attempt of finding a compromise between the productivity of the process and the quality of the manufactured parts (which is intended in terms of density, microstructure, surface finish, and residual stresses).

More specifically, the productivity of AM machines can be evaluated through the build rate, which is directly related to both the laser energy density (a parameter that depends on laser power, scan speed, and hatch distance) and the powder layer thickness (in case of SLS/SLM and EBM) or the deposit rate (in case of DMD). Since part properties such as density and surface finish are closely dependent on the aforementioned process parameters, it is easy to understand how a trade-off is required between the production time and the quality of the 3D-printed part. This is why present small-sized AM machines designed for the dental and jewelry sectors, which require high detail capability, have low productivity values.

Materials Metal powders for laser AM are currently being produced by the use of various processes, which differ in terms of quality of their outputs. Since particles with spherical shape and small size generally lead to better densities and surface finishes than coarser ones, a trade-off exists between the cost of the atomization technique, which reflects on the cost of the metal powder produced by it, and the quality of the manufactured parts.

Software Present AM machines require STL files as inputs for the production of parts, therefore the accuracy of these latter is strongly dependent on the quality of the triangulation of their geometry. Consequently, it is often worth dedicating some time to the manual correction of these files, looking for a compromise between a longer preparation phase of the manufacturing process and both a higher reliability of this latter and a better quality of the 3D-printed part.

Design for AM Additive technologies, avoiding the need of a compromise between optimality and ease of manufacture, allow design optimization through the use of advanced FEM-based software. As described in Chap. 11, this approach makes it possible to obtain parts that are lighter, stronger and typically more energy efficient. A trade-off thus exists between the added computational expense at the design stage and the struggle for optimal performance of the results.

Similarly, the part built orientation and the topology of supports may be optimized so that the considerable waste in terms of material, energy and time employed for their construction and removal is reduced. Here again, a balance between the time spent on this phase and the goodness of its result is needed.

Production costs As explained in Sec. 10.1.1, marginal costs of AM processes are independent from production volumes, thence additive technologies are more cost-efficient than traditional ones only if the number of parts to be manufactured is smaller than a certain threshold, different from one product to another. Since part sizes are the main cost drivers of AM processes, it is easy to understand how a compromise between production costs and dimensions of the manufactured parts should be taken into consideration when possible.

For what concerns fixed cost of metal AM, it is possible to say that prices of AM machines tend to increase with the size and the productivity of such devices. Therefore, the purchase of this kind of equipments has to be carried out on the basis of what part dimensions and regimes of production have to be achieved.

13.2 The "machine of the future" concept development

Starting from the users' requirements (identified in Chap. 3), a list of technical requirements has been derived. In particular, the key aspects that need to be addressed are: surface quality, building volume, build rate, capability to produce functionally graded components, and design freedom, i.e. the flexibility of the process.

The SoA technology is able to address some of the issues concerning these aspects; nevertheless, as they are deeply interwoven (as depicted in Tab. 13.1), an improvement in one feature often results in detrimental effects on the others. In detail, as Tab. 13.2 shows:

- An increase in surface quality can be achieved either decreasing the layer thickness or machining the printed component. However, with the present AM technology, applying one of these solutions will impact negatively the production lead time, reducing throughput and increasing costs. As a matter of facts, a thinner layer implies a longer printing time, because of the higher number of layers to be processed, thus increasing the amortization costs per unit part produced.

	Build Rate	Surface Quality	Build Volume	Mechanical Properties	Production Lead Time	Material Usage	Process Reliability	Process Yield	Cost	Functionally Graded Parts
Build Rate										
Surface Quality	−									
Build Volume										
Mechanical Properties	−	+								
Production Lead Time	+	−	−	−						
Material Usage			−							
Process Reliability		+		+	+	−				
Process Yield		+			+	−	+			
Cost	−	−	−	−	−	−	+	+		
Functionally Graded Parts	−			+					−	

Table 13.1: Interconnection among the key aspects of the present metal laser AM technology and their effect on each other.

PROBLEM/ REQUIREMENT	INCREASE BUILD RATE	PRODUCTION OF FUNCTIONALLY GRADED PARTS	INCREASE SURFACE QUALITY	INCREASE BUILDING VOLUME	INCREASE DESIGN FREEDOM	INCREASE PROCESS RELIABILITY/ PRODUCT QUALUTY
SOLUTION	+ Layer thickness + Laser power	Multi-powder management system	− Layer thickness Post processing (machining)	+ Printing area	+ Degrees of freedom	Trial and error approach
STATE OF ART TRADE - OFF	− Surface quality − Mechanical properties	Not feasible	− Throughpot + Cost + Production lead time	− Material usage	Change of paradigm needed	− Process yield
FUTURE SOLUTION	DD laser Multiple nozzles	DMD with multi-nozzle system	Laser ablation	Direct metal deposition	Direct metal deposition	In-line monitoring

Table 13.2: SoA technology leads to trade-offs that can be broken only through innovative solutions.

- Building volume has to increase, as some end users, as the automotive sector, require bigger parts. In actual PBF machines the part dimension is constrained by the building chamber volume that has to be completely filled. So, in order to increase the printing area, a larger amount of powder material is needed, therefore increasing costs.
- To increase productivity, that is one of the main limitations of the actual AM processes, thicker layers can be deposited and more powerful lasers can be exploited. However, surface quality is negatively affected both by larger layer thickness, that may create scalloped surfaces, and by a more powerful laser source, that, with the SoA technology, would result in an increase in the beam spot size. Moreover, these two solutions would also worsen mechanical properties. Indeed, a thicker layer or a larger spot would imply a decreased laser energy density during the deposition process, and thus a lower part densification.
- With actual AM technologies, moreover, the possibility to build functionally graded components, that could be interesting applications to be exploited in different fields, such as in the aerospace field, is just being tested with DMD technologies, and it's impossible with PBF.
- Process reliability and parts quality are a pending issue in present AM technologies, which can be partly addressed by using a trial and error approach: an iterative process in which a set of parameters is adjusted on the basis of the part printing result until an acceptable part quality is reached.
- Currently, using AM, it is impossible to reach tight tolerances suitable for mechanical coupling.

In the team's vision, the "machine of the future", capable of overcoming these problems and breaking some of the trade-offs listed in the previous section, will integrate a new set of features.

Firstly, it will employ advanced DMD technology, in order to be able to produce large components without filling with powder material the printing chamber.

Secondly, to increase build rate and produce functionally graded parts, the machine will be based on a multi-nozzle system. The presence of multiple nozzles will ensure a coherent and symmetric flux of powder, which will be homogeneously impressed by the laser beam. The multiple nozzles will allow ejecting a large material amount, as well as the possibility to deposit different materials at the same time, thus creating mixtures.

Thirdly, provided that a technology advance in fiber lasers is reached, the machine will be equipped the next generation of fiber lasers, the direct diode laser source, capable of retaining the spot size typical of the hundreds Watt sources, while operating in kilowatt regimes. The new power source will allow for a build rate increase, without compromising surface quality. High surface quality will be obtained by adding an innovative laser system able to perform the surface refinement through ablation. This way, the machine will have a scanning head able to simultaneously handle two different laser beams: the first, used for metal sintering and designed to increase deposition rate; the second, coming from a pulsed laser source used to achieve very high surface quality through controlled precisely controlled ablation.

In order to ensure a higher design freedom, the machine head movements will realize fast and precise movements, relying upon 5 Degrees of Freedom (DoF). This redundant combination ensures the possibility to realize concurrently large movement ranges for big parts while processing very small spots requiring small (often micro) and precise features.

Developing in-process monitoring and control methodologies will allow for in-line adjustment of process parameters through real-time 3D scanning of the produced component, pursuing the objective of zero faulty parts delivered.

Lastly, in order to guarantee adequate tolerances, machining is necessary. Therefore, a possible solution is the integration of a subtractive head in the machine performing CNC milling where it is needed, such as on the component functional surfaces. This process will provide a lot of flexibility, as it allows alternating between additive and subtractive operation to manufacture the part.

Tab. 13.3 reports a comparison between three different solution concepts, referred to the SoA benchmark values. The key parameters considered for the evaluation are: surface quality, build rate, build volume, material usage, ability to produce functionally graded parts, the possibility to integrate traditional and additive technologies, design freedom, and self-resilience of the machine.

The "Enhanced PBF" technology represents an improvement with respect to the SoA PBF technology by using multiple and more powerful laser sources, such as direct diode ones, and larger printing areas. However, the economic feasibility of this solution is compromised by the large materials usage, while the technical feasibility is limited by the low number of DoF available and by issues regarding the realization of a laminar flow of protective gas over large areas. Moreover, it would be impossible to manufacture functionally graded parts and to perform a real-time 3D scanning of the printed component, which would enable closed-loop control. Therefore, the LAMP team believes that enhanced PBF does not represent the future of AM machines.

The "Hybrid Subtractive-Additive technology", which embraces the DMD paradigm, represents a leap forward with respect to the SoA PBF technologies. It is based on a CNC machine integrating in its revolver an AM head for laser deposition and cladding. Consequently, printing volumes, DoF and material usage benefit of this shift in technology, which also enables closed-loop control through 3D scanning and repairing of damaged parts. Moreover, the integration of CNC milling capabilities lead to improved surface quality of the resulting components. A major advantage is that manufacturers can immediately, in the same set-up, machine the functional surfaces to complete the part for final use. However, firstly, functionally graded parts are not feasible with current DMD technology employing single nozzles; secondly, the build rate growth may not be fast enough to meet the requirements of some users, such as the automotive sector.

"Enhanced DMD" refers to the previously described evolution in current DMD technology, by means of a multi-nozzle feeding system, a relevant innovation in the laser power source, allowing for a build rate increase and the integration of the laser ablation function.

According to the team's analysis, the "Enhanced DMD" concept, if complemented with the "Hybrid Subtractive-Additive" technological solution, has the potential to become the winning paradigm of the future. In fact, as the "Enhanced DMD" technology has resulted to be the best concept in every field, with the only drawback being the inability to meet tight tolerance requirements, the integration with CNC milling performed by a subtractive head would enable the fulfillment of such requirement and the avoidance of further post-processing (with the exception of stress relieving heat treatments, when needed).

13.3 Feasibility analysis and concept evaluation

The economic impact of the AM machine concept developed by the LAMP team can be estimated assuming its commercial exploitation.

To determine a feasible market price, a preliminary analysis of market positioning of the team's concept has been performed based on market data from [4] and from market researches performed by the industrial partner of the project. A possible consistent positioning of the proposed product in respect to

	KPI	Enhanced DMD	Hybrid Subtractive-Additive Concept	Enhanced PBF	SoA benchmark
Concept description		-Direct Metal Deposition - Multi-nozzle - Laser ablation	-Multiple-head system -CNC milling combined with laser cladding	-Powder Bed Fusion -Multiple laser sources	-PBF single energy source -DMD single nozzle
Surface quality	Surface roughness	++	++	+	1-10 μm
Adequate tolerances	-	N	Y	N	N
Build rate	Deposited material per time unit	+++	+	++	< 5 kg/h
Build volume	Printing chamber volume	+++	++	+	Max 0.5x0.5x0.2 m
Material usage	Product weight /Material used in the process	++	+	=	5% in PBF, 70% in DMD
Functionally graded parts	-	Y	N	N	N
Design freedom	Number of DoF	5	5	3	3 in PBF, 5 in DMD
Complex product repair	-	Y	Y	N	N in PBF, Y in DMD
Self-resilience of the machine	Closed-loop control based on in-line 3D scanning of the part	Y	Y	N	N

Table 13.3: Comparison between three different solution concepts, referred to the SoA benchmark values.

the market situation is given in Fig. 13.1.

According to the team's analysis of the predicted performances for its concept device, and considering its cost compared to that of present technologies, the price for the machine is set to be EUR 950.000, which is believed to be sustainable by the market in the present business case, as it preserves the present performance/cost ratio.

In this context, the economical feasibility analysis is carried out using two different approaches:

- A top-down approach, that, starting from current AM market size and the new machine concept positioning with respect to current AM machines, tries to understand the market share that it will be reached after the product launch. According to the achieved market share, it is possible to estimate the revenues per year; operating cash flows are obtained complementing the analysis with production costs.
- A break-even analysis (bottom-up approach) allowing the team to understand how many machines have to be sold in order to recover from expenses.

13.3.1 Top-down approach

The current specific market is estimated to be around 540 machines per year, which, according to the data reported in [3], correspond to the total amount of sold machines in 2014. The market size growth is reported to be in the order of 20%, or even 30%, depending on the source and the period considered. In the cash flow analysis a conservative estimate of 15% market growth on a yearly basis has been taken into account. Considering the market segmentation with respect to machine performances, the LAMP concept machine could target a market share in between 3% and 7% - according to the estimates of the project's industrial partner. Here three different cases are reported: the base case, in which 5% market share is attained, the worst one in which a market share equal to 3% is reached, and finally the best case in which the target of a 7% market share is achieved. Therefore, in the base case 54 machines will be sold in 2020, while in the worst and best cases that figure will change to 33 and 76 machines, respectively.

A first analysis of production cost based on the experience of the external partner leads to the following estimates:

- 250,000 EUR for machine structure;
- 100,000 EUR for AM multi-nozzle head;
- 50,000 EUR for the subtractive head and revolver system;
- 200,000 EUR in laser sources;
- 100,000 EUR for numerical control;
- 20% of the revenues for marketing and distribution.

The cumulated cash flow in the base case scenario (Tab. 13.4) with a 5% market share, without considering any funding support, gives a break-even in 2021. After break-even the estimated cost structure could give an interesting gross profit of 1,653 kEUR/year, which could be a stable base for further investment to improve both the product and the market share.

Tab. 13.5 shows the results of a sensitivity analysis performed for the three considered scenarios. As it is evident, only the worst case scenario does not lead to a positive cumulated cash flow at the end of 2021, while both the base and best case result in a profitable investment.

Base Case Scenario

		2015	2016 (E)	2017 (E)	2018 (E)	2019 (E)	2020 (E)	2021 (E)
Market size	Machine number	540	621	714	821	944	1086	1249
Market share	%	0	0	0	0	3.0%	5.0%	5.0%
Production volume	Machine number	0	0	0	0	28	54	62
Unit Price	k €	€ 950	€ 950	€ 950	€ 950	€ 950	€ 950	€ 950
Sales Revenues	k €	€ -	€ -	€ -	€ -	€ 26,917	€ 51,591	€ 59,330
R&D	Number of employees	0	0	0	2	2	2	2
Management	Number of employees	0	0	0	1	1	1	1
Blue collar	Number of employees	0	0	0	0	20	30	40
Labor cost	k €	€ -	€ -	€ -	€ 122	€ 602	€ 842	€ 1,082
Overhead	k €	€ 55	€ 55	€ 55	€ 75	€ 75	€ 75	€ 75
Structure and axis	k €	€ -	€ -	€ -	€ -	€ 7,083	€ 13,577	€ 15,613
Metal multi-nozzle deposition head	k €	€ -	€ -	€ -	€ -	€ 2,833	€ 5,431	€ 6,245
Laser source	k €	€ -	€ -	€ -	€ -	€ 5,667	€ 10,861	€ 12,491
NC	k €	€ -	€ -	€ -	€ -	€ 2,833	€ 5,431	€ 6,245
Milling head		€ -	€ -	€ -	€ -	€ 1,417	€ 2,715	€ 3,123
Material cost	k €	€ -	€ -	€ -	€ -	€ 19,834	€ 38,015	€ 43,717
Other direct costs (energy,...)	k €	€ -	€ -	€ -	€ 6	€ 425	€ 815	€ 937
Total direct cost	k €	€ 55	€ 55	€ 55	€ 203	€ 20,936	€ 39,746	€ 45,811
Marketing and distribution cost	k €	€ -	€ -	€ -	€ -	€ 5,383	€ 10,318	€ 11,866
Start-up expenses R&D	k €	€ 270	€ 270	€ 270	€ 135	€ -	€ -	€ -
Start-up expenses manufacturing	k €	€ -	€ -	€ -	€ 700	€ 600	€ -	€ -
Cash Flow IN	k €	€ -	€ -	€ -	€ -	€ 26,917	€ 51,591	€ 59,330
Cash Flow OUT	k €	€ 325	€ 325	€ 325	€ 1,038	€ 26,919	€ 50,065	€ 57,677
Cash Flow Delta	k €	- € 325	- € 325	- € 325	- € 1,038	- € 2	€ 1,527	€ 1,653
Cumulated Cash Flow	k €	- € 325	- € 650	- € 975	- € 2,013	- € 2,015	- € 488	€ 1,165
Present value of cash flow delta		- € 325	- € 295	- € 269	- € 780	- € 1	€ 948	€ 1,027
NPV	304							

Table 13.4: Base case scenario analysis.

Sensitivity Analysis

	2015	2016 (E)	2017 (E)	2018 (E)	2019 (E)	2020 (E)	2021 (E)
Market Share	%	%	%	%	%	%	%
Base case	0%	0%	0%	0%	3%	5%	5%
Best	0%	0%	0%	0%	5%	7%	7%
Worst	0%	0%	0%	0%	2%	3%	3%
	2015	2016 (E)	2017 (E)	2018 (E)	2019 (E)	2020 (E)	2021 (E)
Machines Sold	#	#	#	#	#	#	#
Base case	0	0	0	0	28	54	62
Best	0	0	0	0	47	76	87
Worst	0	0	0	0	19	33	37
	2015	2016 (E)	2017 (E)	2018 (E)	2019 (E)	2020 (E)	2021 (E)
Sales Revenues							
Base case	0	0	0	0	26917	51591	59330
Best	0	0	0	0	44862	72228	83062
Worst	0	0	0	0	17945	30955	35598
	2015	2016 (E)	2017 (E)	2018 (E)	2019 (E)	2020 (E)	2021 (E)
Cash Flow Delta							
Base case	-325	-325	-325	-1038	-2	1527	1653
Best	-325	-325	-325	-1038	848	2504	2778
Worst	-325	-325	-325	-1038	-427	549	529
	2015	2016 (E)	2017 (E)	2018 (E)	2019 (E)	2020 (E)	2021 (E)
Cumulated Cash Flows							
Base case	-325	-650	-975	-2013	-2015	-488	1165
Best	-325	-650	-975	-2013	-1165	1339	4117
Worst	-325	-650	-975	-2013	-2440	-1891	-1361

Table 13.5: Sensitivity analysis for the base, best and worst case scenarios.

Break Even analysis

Unit price of LAMP machine (k€)	950	
Fixed Costs (k€)		
Start-up expenses manufacturing	600	
Labor cost	602	
Overhead	75	
	1277	
Variable Costs (k€)		
Components cost	700	
Marketing and distribution cost	190	
Other direct costs (energy,...)	15	
	905	
Break Even Point	28	units

Table 13.6: Break-even point analysis for the base case scenario.

The outcome of the sensitivity analysis results to be even more satisfactory if one considers the fact that no European funding was taken into account in the analysis. However, the European Union has foreseen a considerable investment in projects related to the additive manufacturing technology; therefore, the team's concept would be eligible for public funding.

13.3.2 Bottom-up approach

Within the base case scenario, a break-even analysis is carried out in order to find the number of machines to be sold in order to cover fixed costs, evaluated with respect to 2019, which is the year in which commercialization is due to launch. In the team's analysis, fixed costs comprise start-up expenses for R&D and manufacturing, overhead and labor costs. Variable costs consists of materials, direct costs such as energy, marketing and distribution expenses (which are evaluated as a percentage of revenues).

As Tab. 13.6 shows, break-even point is reached at 28 units sold.

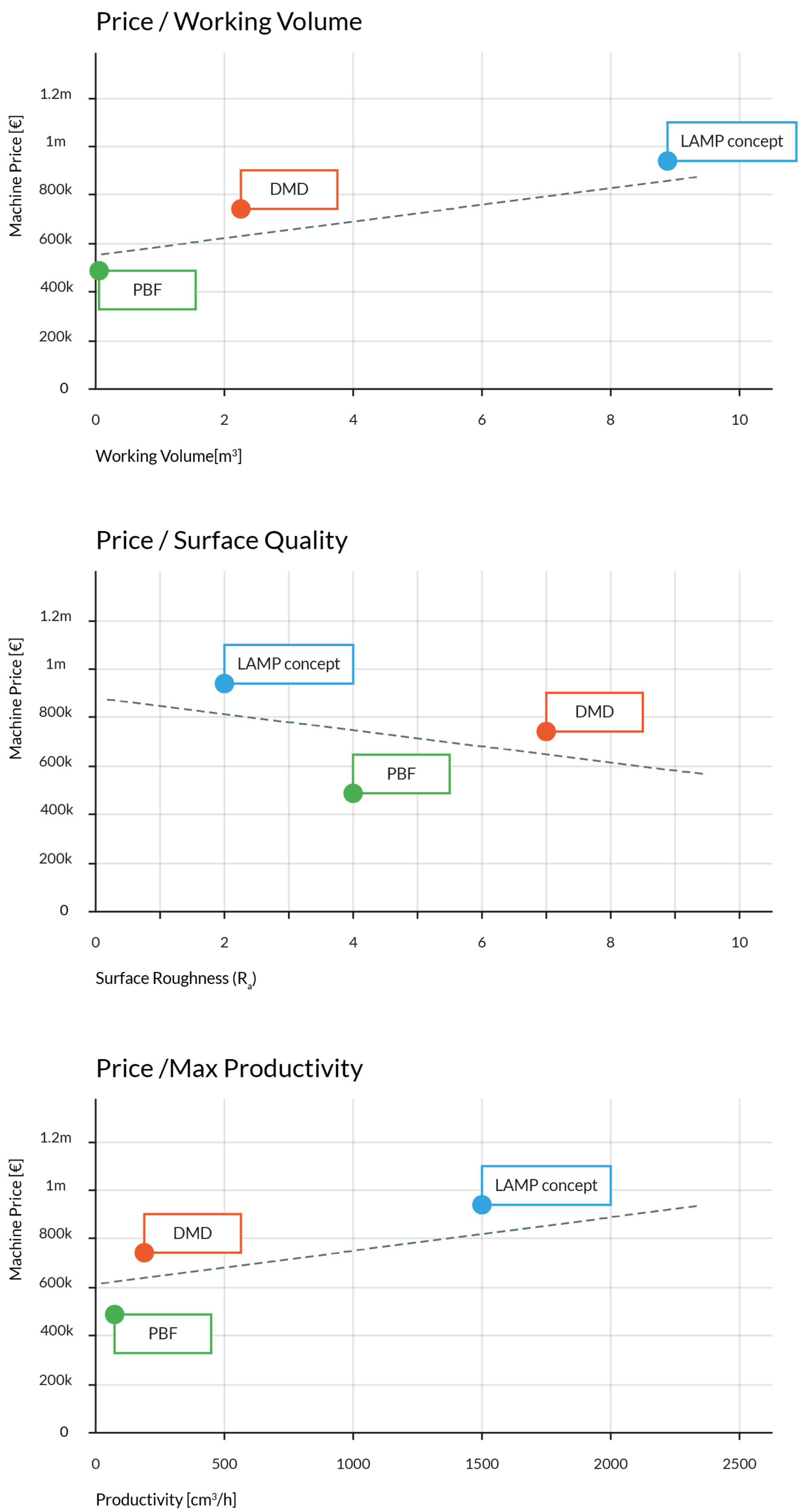


Figure 13.1: Concept price positioning with respect to three key performance indicators.

Conclusions

AM is a technical innovation with the potential to turn around the way in which companies manufacture end-products and do business, giving a new shape to both internal and external processes (concerning the firm-client relationship). By overcoming the limits imposed by conventional production techniques, AM is opening up new thrilling possibilities for the aerospace, automotive, biomedical and other sectors, as it allows the user to turn virtually any conceivable shape into a real product, with the minimum use of material. Indeed, this technology is not subject to any design restriction thanks to its layer-by-layer approach which makes it possible to produce complex geometries (i.e. structures that often feature undercuts or hollow spaces) without the need of additional fixtures.

In this regard, the possibilities opened by AM allow to design parts that are optimized for their function. For instance, the creation of elaborated shapes, such as lattice structures, impossible to be obtained with traditional manufacturing techniques, may lead to components that are fully optimized from a strength-to-weight standpoint. On this subject, the case study presented by the team provides a good example of how the structural optimization process can be applied in order to obtain a lighter and more energy efficient part.

However, state of the art technologies have faced few technological trade-offs and encountered several issues in satisfying stakeholders' needs. In particular, limited printing volumes, low deposition rates and poor surface qualities are the main factors that have limited so far the diffusion of AM at large scale. In this scenario, our industrial partner *Prima Industrie* wants to develop a revolutionary metal 3D printer exploiting its present know-how in the field of high power laser sources and industrial machinery.

The "machine of the future" concept developed by the team is capable of breaking the examined trade-offs by integrating a multi-nozzle Direct Energy Deposition system with a direct diode laser source, capable of processing multiple materials at the same time, a laser ablation system for surface quality improvement, a closed-loop control system to constantly monitor process parameters and a machining head. Regarding the feasibility of the project, the analysis carried out by the team has shown a potentially profitable investment.

The commercial launch of AM machines capable of breaking existing trade-offs will boost the AM business and help to get acceptance in new markets and by new industries. However, for the LAMP concept to become technologically feasible, fundamental breakthroughs have to be achieved in the laser field, in order to enable the use of both the direct diode technology and the laser ablation application, through advances in research and development. At the same time, the AM technology needs to evolve simultaneously on all technological fronts, improving the performances of its processes. To this purpose, both the public and the private sector are investing in this emerging technology, pushing forward its development. Obviously, since the technology is relatively new, and it is rapidly improving, the technical assessment of laser sources, powders, software and fields of application provided in this report will need to be continuously updated.

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