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ADDITIVE MANUFACTURING TECHNOLOGY - CHALLENGES AND OPPORTUNITIES IN COVID-19 PANDEMIC TIMES

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Abstract: Additive Manufacturing is a technology for manufacturing finished products, layer by layer. It is different from conventional processes, such as stamping / casting. It is a computer system, using projects in Computer Added Design that use 3D printing to join different materials to the final product of the form, through heat and other processes, such as the final application. The materials used are ceramic, metallic and polymeric micro / nanometric powders or a mixture of them. It was in the mid-80s of the 20th century that developments of this technology began. Additive manufacturing is of great importance for industries, as it eliminates the models / stamping molds / forging tools and molds / molds, because the goods are manufactured in their final geometry. The challenges are the cost of production and quality of the produced part, which must have the same or better performance than that manufactured by conventional methods. In the midst of the Covid-19 pandemic that hit 2020, additive manufacturing came as an aid to create personal protective equipment such as visors produced by companies, educational and research institutions or ordinary citizens. The present work presents this technology, its challenges and the beneficial aspects that it can generate for humanity in Covid-19 times and after.

Keywords: Additive Manufacturing. Technology. Additives. Materials. Challenges. Pandemic. Covid-19.

Nomenclature

3DP – 3 Dimensional Printing
BJ – Binder Jetting
AM – Additive Manufacturing
DED – Direct Energy Deposition
DMD – Direct Metal Deposition
DMLS – Direct Metal Sintering
LOM – Laminated Object Manufacturing
LMD – Laser Metal Deposition
ME – Material Extrusion
MJ – Material Jetting
MJS – Multiplayer Jet Solidification
NASA – National Aeronautics and Space

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DLF – Direct Light Fabrication
DP – Direct Printing
EBM – Electron Beam Melting
EBAM – Electron Beam AM
FEF – Freeze-form Extrusion Fabrication
FDM – Fused Deposition Modeling
LAM – Laser Additive Manufacturing
LBM – Laser Beam Melting
LENS – Laser Engineered Net Shaping
Administration of the U.S.A.
PBF – Powder Bet Fusion
PDB – Plate Diffusion Brazing
PJM – Polyjet Modeling
SLA – Stereography
SM – Sheet Lamination
SLM – Selective Laser Melting
SLS – Selective Laser Sintering

1. Introduction

Many researchers Additive Manufacturing [1-16], some citing standards [1-6, 8, 11-13] and others not [7, 9, 10, 14-16]. Of those who take the norm as the primary source of reference, only two authors [3, 8] cite the current standard and that has been active since 2015. This fact does not detract from the research of any of them, however, it is a point of attention when referring to norms and standards, and it is always necessary to adopt the current and active.

Therefore, the definition of Additive Manufacturing is given by the standard current and active ISO ASTM 52900-15 [17] as “process of joining materials to make parts from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing and formative manufacturing methodologies”.

So, this technology involves the knowledge and selection of materials and processes and their applications in final goods. As with all technology, there are always positive and negative factors, i. e., advantages and disadvantages, as well as challenges and opportunities for improvement.

This paper discusses this AM technology, along with the materials, process, applications and challenges that guide its evolution and the beneficial aspects that it can generate for humanity in Covid-19 times and after.

2. Development

AM materials, processes and applications are presented below. The AM processes and their applications will be presented and how they will impact the materials used. For each type of material, a basic and effective configuration must be determined.

2.1. Materials

Several researchers [6, 7, 14, 18] present the classes of materials: polymers, metal, ceramics and composites. Lehmus et al [18] also cite about novel steel grades and advanced aluminum alloys, while Jimenéz et al. [8] cite about polymers, but for space applications.

Hegab [7] that the additive manufacturing (AM) technology, started with plastic prototypes using various AM Process, such as Fusion Deposition Modeling (FDM), Stereolithography (SLA) and other processes. After more research and development, AM can be used other materials, including metals, ceramics, and composites. This researcher [7] consider that polymers and metals are as commercially available materials for AM processes, but, ceramics and composites are under research and development. He studied composite materials such as nanocrystalline titanium carbide (TiC)-reinforced with Inconel 718 matrix, and potential alloys.

Other researchers [1, 3, 11, 18] metal feedstocks such as Ti6Al4V alloy. It is important to note that, according to ISO ASTM 52900-15 [17] "feedstock is a bulk raw material supplied to the Additive Manufacturing building process".

Azam et al. [1] used data from several literature to compose a table of mechanical properties for the Ti6Al4V alloy.

They comment that one process had mechanical properties better than the other (EBM better than SLM), but these results are all equivalent when compared with the minimum values specified by ASTM F136-08, which was not presented in their paper. Of the data they used, only Cast material does not meet the Yield Strength (YS, MPa) and Ultimate Tensile Strength (UTS, MPa) standard, but only Wrought and EBM meet all the requirements of the standard, including Elongation (%) for all references [1].

Körner [10] cites metal and alloys, Zadi et al. [15] present steel fabrication and Ti alloy and Ni-Base alloys, and Elahinia et al [19] present a NiTi alloy.

Lehmhus et al. [18] present composite, TiAl6V4, pure Fe, pure Al and advanced aluminum alloys (AlSi10Mg, AlSi12).

Gardan [20] cites smart materials and Dilberoglu et al. [21] cite metals, composites, smart materials and special materials such as concrete, textile, etc.

2.2. AM Processes

Some researchers [1, 6, 10, 18] comment that for each material there is a specific process of AM.

Lehmhus et al [18] reveal that all AM process has by now been adapted to several material classes. Table 1 (adapted) provides an overview of process by material class and these data should be read with care because new combinations or the process are constantly emerging [18].

Table 1 - Overview of process AM by material class (adapted) [18].

Process Class	**Process**	**Polymer**	**Metal**	**Ceramic**	**Composite**
Binder Jetting (BJ)	3D Printing (3DP)	X	X	X	X
Direct Energy Deposition (DED)	Laser Engineered Net Shaping (LENS)	-	X	X	X
	Direct Light Fabrication (DLF)	-	X	-	-
	Direct Metal Deposition (DMD)	-	X	-	-
Material Extrusion (ME)	Fused Deposition Modeling (FDM)	X	X	X	-
	Multiplayer Jet Solidification (MJS)	-	X	-	-
	Robocasting	-	-	X	-
	Freeze-form Extrusion Fabrication (FEF)	-	-	X	-
Material Jetting (MJ)	Multijet/Polyjet Modeling (MJM/PJM)	X	-	-	-
	Direct Printing (DP)	X	X	X	-
Powder Bet Fusion (PBF)	Laser Beam Melting (LBM)	-	X	-	X
	Selective Laser Sintering (SLS)	X	X	X	X
	Direct Metal Sintering (DMLS)	-	X	-	X
	Electron Beam AM (EBAM)	-	X	-	-
Sheet Lamination (SM)	Laminated Object Manufacture (LOM)	X	X	X	-
	Plate Diffusion Brazing (PDB)	-	X	-	-
Vat Photopolym.	Stereolithography	X	X	X	X

2.2.1. Selective Laser Melting (SLM)

SLM is one of the industry's leading additive manufacturing technologies. It is precise and fast compared to other AM Technologies [1]. SLM using Argon as shielding gas [10]. See Figure 1 [1].

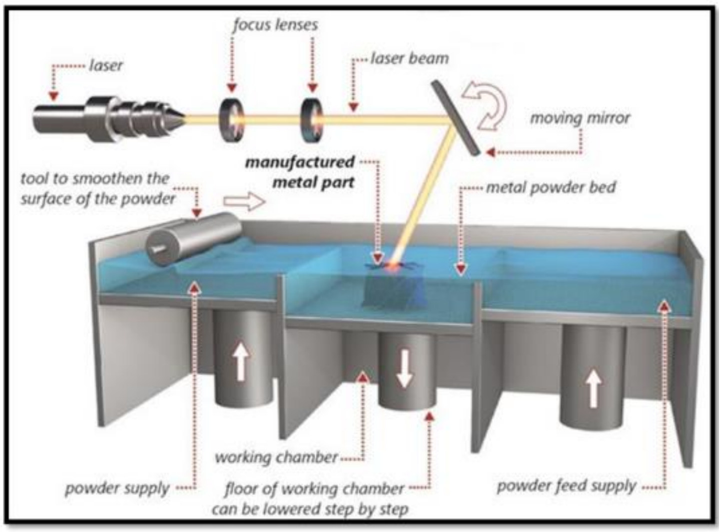


Figure 1 – SLM process [1].

2.2.2. Electron Beam Melting (EBM)

EBM is another additive manufacturing technology which forms 3D parts by full melting of powder particles. The key difference between laser, based additive manufacturing technologies, and EBM is the heat source [1]. EBM uses an electron beam instead of a laser, which requires that the procedure for EBM is carried out under vacuum conditions [1, 10, 15, 16] to prevent dissipation of the electron beam. See Figure 2 [1].

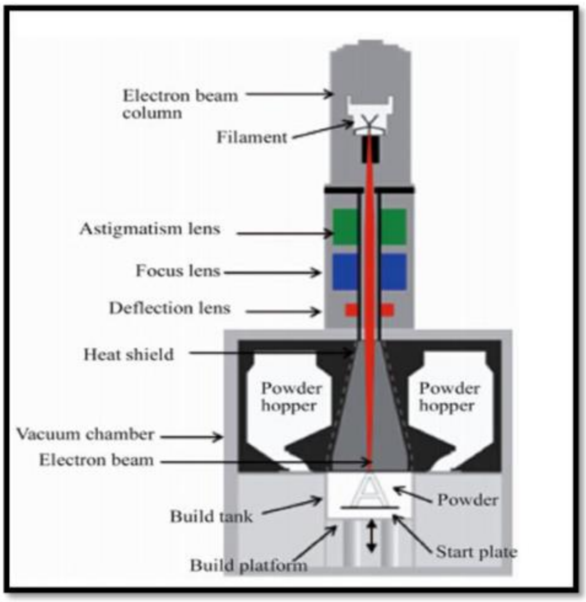


Figure 2 – EBM process [1].

2.2.3. Laser Metal Deposition (LMD)

LMD also called as direct energy deposition (DED) and laser cladding, is a powder, based additive manufacturing process, which is used to build 3D parts, repair metal components deemed nonrepairable by conventional methods or add features to existing parts. The process is very simple and it begins with a 3D model like other AM technologies. See Figure 3 [1].

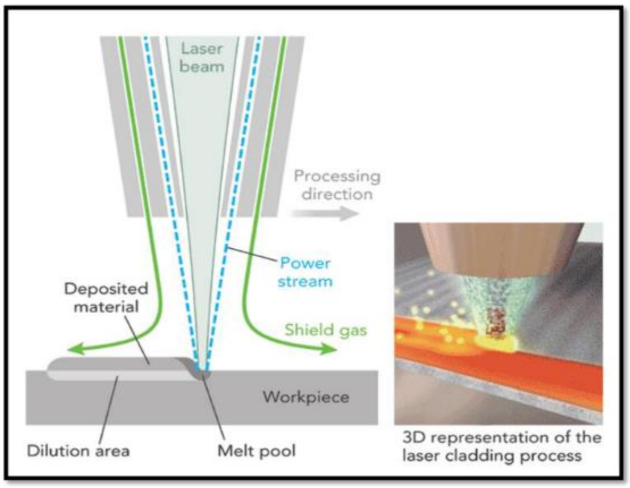


Figure 3 – LMD process [1].

Körner [10] presents that SLM can be used for metals, polymers and ceramics, while EBM works under vacuum conditions, with high velocities and a high beam power, is restricted to metallic components, because source electric conductivity is required.

Lehmus et al [18] show LBM mechanical properties data of many materials, but haven't standard specifications.

Liu et al [11] cite Ti6Al4V fabricated by DED, SLM and EBM. They made a table of mechanical properties of Ti6Al4V by DED, SLM, EBM, Forged and Cast using several references from the literature and the standard specifications (ASTM F136).

Zadi et al [15] show that EBM can provide higher scan rate up to 10^4 mm/s while LBM that only 1200 mm/s. For EBM there is few studies for steel, but is popular for Ti Alloy and Ni-Base Alloys [15].

2.3. Applications

The researchers' review papers [2, 7, 8, 11, 20] present some AM applications.

Hegab [7] presents applications for automotive, biomedical, aerospace. Aerospace applications haven't been limited by using only metals, as ceramic parts are used especially ultra-high temperature ceramics which can withstand more 2273 K. Examples of aerospace ceramic parts are hypersonic flight systems and rocket propulsion systems which have more complex geometries using SLS process.

Liu et al [11] show biomedical and air duct made of Ti6Al4V fabricated by EBM and SLM, respectively.

Gardan [20] presents applications aeronautics, architecture, automotive industries, art, dentistry, fashion, food, jewellery, medicine, pharmaceuticals, robotics and toys.

See in Figure 4 follow, the percentage of the industrial sectors using AM [2, 8].

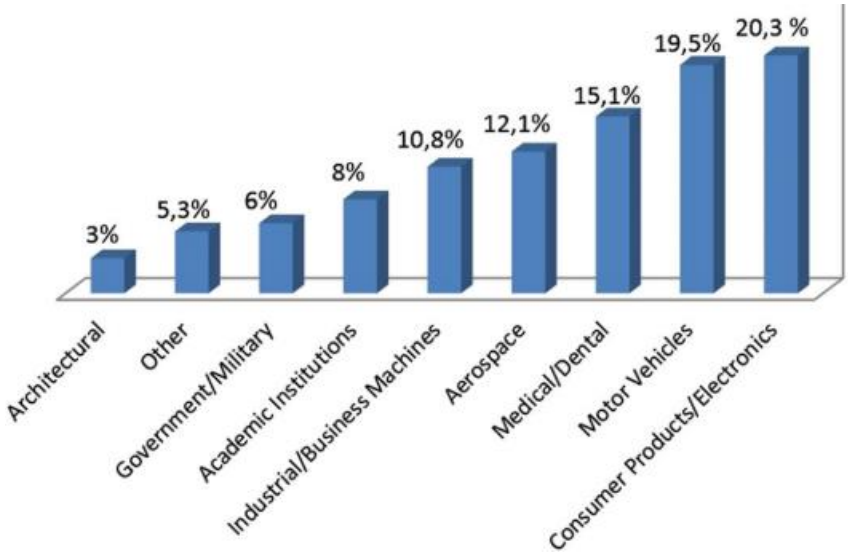
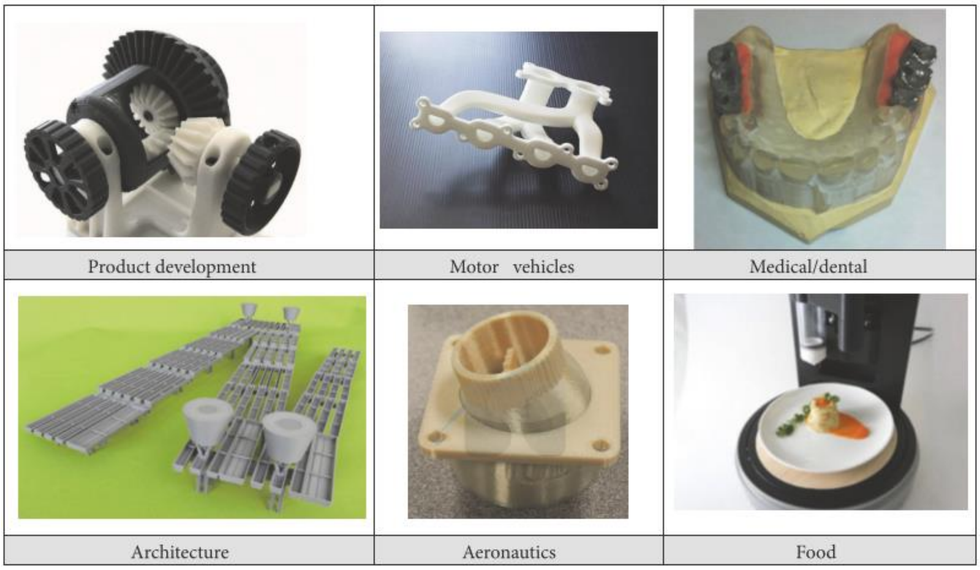


Figure 4 – Percentage of the industrial sectors using AM [2, 8].

Jimenéz et al [8] summarize some of the possibilities of AM applications (see Figure 5).



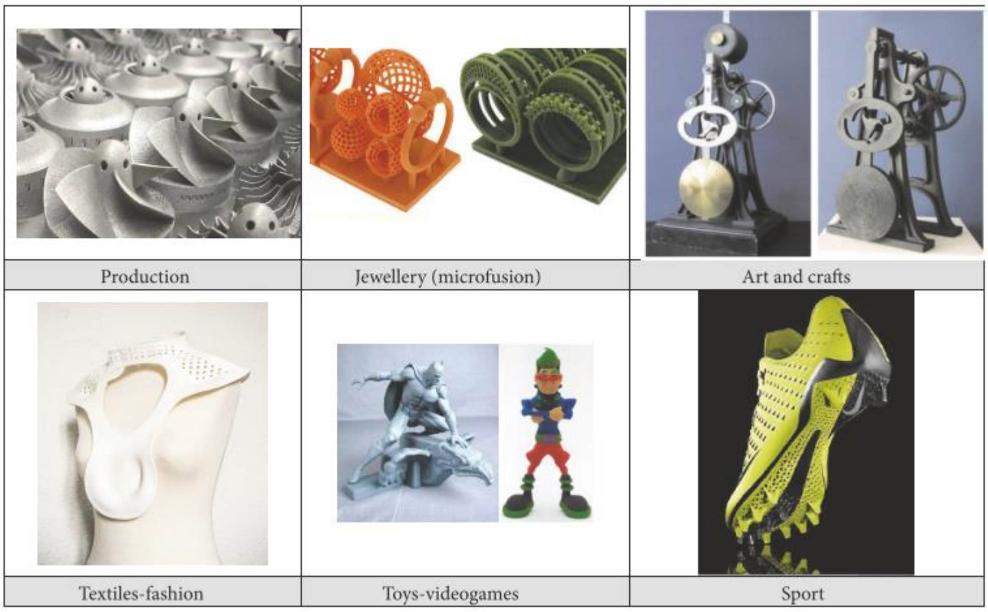


Figure 5 – AM applications [8].

3. Advantages and Disadvantages, Trends and Opportunities / Challenges

Advantages are, in some way, associated with trends and disadvantages to opportunities for improvement and / or challenges to be overcome.

3.1. Advantages and Disadvantages

The researchers [2, 4, 7, 8, 10, 14, 15, 18] present the AM advantages:
- More flexible development [4, 10, 14];
- Freedom of design/complexity geometry [4, 7, 8, 10, 15, 18];
- Less assembly [4, 18];
- No production tool [4, 8];
- Production small quantities/economic low volume production [7, 8, 10, 15];
- Reduction time to launch a good in the market[4, 14] ;
- Environmental sustentability/reduce waste [2, 7, 14, 15] and
- Weight reduction/reduce cost [10, 15].

The AM disadvantages [4, 8] are showed by:
Costabile et al [4] as:
- High costs of machine and feedstocks and
- Rework is often necessary.

And Jiménez et al [8] as:
- The finish of complex surfaces can be extremely rough;
- Long production times;
- Materials with limited mechanical and thermal properties which restrict performance under stress and
- Higher tolerances than with other manufacturing methods such as those based on material removal.

3.2. Trends, Opportunities and Challenges

Researchers [7, 8, 10, 18] agree that AM is a revolutionary industrial process to goods' or components' production.

3.2.1. Trends

The researchers cited initially [7, 18, 20] in their review papers, add other researchers [2, 3, 21] who also cite trends.

Hegab [7] presents trends for the future:
- More potential users will lead to low or medium cost AM systems.
- Increase of materials and process through increasing the speed of processing.
- The capability of processing multiple materials within the same AM system.

Lehmhus et al [18] present that future trends in AM are:

- Advanced Alloys: where the growing diversity of materials processed through AM techniques are considerable advances have been made regarding alloy development AM processes, such as novel steel grades, and advanced aluminium alloys with enhanced properties.

- Multi-Material Solutions: through the possibility to change a part's internal structure has fuelled massive interest in AM as the major tool for the realization of tailored materials developed using computational materials science techniques, optimizing properties both the micro- to the macroscopic scale.

Gardan [20] presents that trends in smart material are:

- Biomedical: Bio AM or 3D bioprinting shows significant promise for creating complex tissue and organ mimics to solve transplant needs and to provide platforms for drug testing and tissue morphogenesis can be fabricated, yielding advanced porous thermoplastic polymer scaffolds, layered porous hydrogel constructs, as well as reinforced cell-laden hydrogel structures.

- Textile: To design a textile product that can adapt to heat or moisture to improve comfort and to develop new functionalities.

- Aerospace: NASA has used AM to fabricate some rocket parts, and their tests show that AM can save time and reduce costs by 60% or more.

Bikas et al [2] show that AM is a technology rapidly expanding on a many of industrial sectors. In terms of materials processed, plastics are currently leading the AM market, but the metal AM market is also growing and in the last few years, there is a significant trend towards metal AM for the production of structural components, mainly in areas, such as aerospace and motorsport applications, that built from metal.

Brandão et al [3] discussed that in the aerospace area a trend for future missions is that many more components are envisioned to be manufactured using AM, with the production of these goods or parts in orbit.

Dilberoglu et al [21] present that AM is a key technology of the industrial revolution and provides manufacturing opportunity in a broad range in terms of its material (polymers to metals), size (nanoscale to large parts), and functionality (self-assembling to optimum heat transfer).

Dilberoglu et al [21] also cite that another future direction about AM is the sustainability issue, in which AM may play a significant role in diminishing waste resources and reducing energy consumption by employing just-in-time production.

Moreover, the AM may expectedly have an impact on the society where the role of the employee in the industry is to be redefined such that they perform jobs about management/design/analysis rather than being labor force and the platforms like do-it-yourself and maker can involve, integrate users. In the future, the manufacturing business will be distributed to many separate locations like small workplaces or homes. In other words, the current barrier of mass production on location will be overcome with personal and customized fabrication [21].

3.2.2. Opportunities and Challenges

Brandão et al [3] emphasize that dominating Space (outside the Earth) is a great opportunity and challenge for AM regarding cost savings and performance increase.

Ford et al [6] cite what seems like a brainstorming of various ideas, because of a big amount of data, that a more detailed discussion of each item, for example, certifying new components, certifying materials, validating material properties, and others.

Tofail et al [14] present that the challenge is transfer AM into obtaining objects that are functional. It is necessary much work to study the challenges related to the materials and metrology to achieve this functionality [14].

Klocke et al [9] show that for Laser Additive Manufacturing (LAM) there are opportunities and challenges (see Table 2).

OPPORTUNITIES	CHALLENGES
Simple product development	Restricted variety of materials
Unique design flexibility	Unusitable for large scale
Manufacturing customization	Undefined process standards
Applications in new industries	Confidentiality issues
Green manufaturing	Ethical concerns (e.g., guns)

Table 2 – LAM opportunities and challenges [9].

Lehmhus et al. [18] that a critical challenge in manufacturing of metallic materials via AM technology is of whether AM parts can compete, in terms of mechanical properties, with their counterparts made from conventional manufacturing processes like casting and forging.

4. Discussion

Always in the light of the cost-benefit ratio, you can evaluate potential opportunities and challenges based on the references used and main topics (Materials, Process and Applications) in this paper to:

4.1. Materials

The materials used in the AM technology are the traditional, such as polymer, metal, ceramic and composites, with metals, metal alloys and ceramics, usually in powders in micro and nanometric sizes agglutinated or not in a polymer. 195

The opportunities and or challenges are:

- Currently, there is more use of AM for polymeric and metallic materials, even so not all metals and alloys and their feedstocks have been developed or researched, which opens up a range for new demands and future goods.

- For metallic materials, it is necessary to ensure that the same part produced by AM technology presents performance equal to or better to those manufactured by conventional methods such as forging. Cost and large-scale production also require developments to become as competitive as conventional processes such as stamping and casting. The shape of the additives, whether powders or powders wrapped in polymers, composite wires or other modes also requires research too.

- There are few references associated with ceramic materials, probably due to the high costs of their fusion. However, it is a possibility of future developments, opportunities for improvement and challenges to be achieved.

4.2. Processes

The AM technology is of great importance for goods and components' modern manufacturing because it eliminates the need for tooling such as stamping or forging and casting models and molds, since the product or component is already manufactured in its final geometry with computational precision.

The opportunities and or challenges are:

- Equipment in which AM processes, binder removal (when applied), sintering and possible subsequent heat treatments are all done in the same chamber or in separate locations, but in series and automated, still need to be developed.

- As mentioned above, Advantages are associated with trends and disadvantages to opportunities for improvement and / or challenges to be overcome. For example, an advantage today of "Freedom of design / complexity geometry" may generate a trend in the marketplace for designers and manufacturers of parts, components, products to prefer AM to conventional processes such as casting. A disadvantage that refers to "High costs of machine and feedstocks" can generate research and development of AM equipment and the manufacture of cheaper feedstocks, which is an opportunity for improvement and a challenge, a goal to be achieved or overcome.

- Manufacture of large parts or components (such as a propeller of Panamax class ship propeller or a commercial airplane turbine), it will be a possibility to be evaluated and the AM machine chamber must be big also to contain such a component, and there is a need to develop equipment that guarantees precision, quality and speed of production.

- Very small parts, micro or nanometric size also need to develop equipment capable of guaranteeing functionality and durability of these. The manufacturing of ever smaller components with micro or nano precision can open another frontier in several areas such as a medical robot or microsatellites for various uses and with the guarantee of lower energy consumption, reduction of the use of feedstocks, reduction or disposal of waste, cost reduction. For this to occur the laser diameter also needs to be decreased and accurately.

- Having equipment with several lasers or electrons beam that can manufacture several and or differents components simultaneously and, if necessary, subsequent processes that are done in the same chamber or in sequence, serially and in an automated way, can solve the problem, the disadvantage of large-scale manufacturing.

4.3. Applications:

Developed materials, processes, dimensions and costs the applicability of this technology is total, i.e., in all areas, from aerospace, war, automotive to everyday products like a spoon, a mug or a pencil.

In the case of fabrication in Space, which is already happening today, there is no need to take several pieces for Space, only feedstocks are transported, as well as AM equipment and others such as extruders, ovens, etc., since the which has been produced may after some time be recycled and transformed into a new component or part, and continuously.

The opportunities and or challenges are:

- Satellites can also be made in Space or on Earth, miniaturized through AM technology and taken to Earth orbit.

- Use in biomedical applications in which the implant is not made of a metallic or polymeric material, but for example of material as similar as possible to the human bone or skin and with all the characteristics and properties of the original can be a great challenge not only for AM technology as well as for ethics and morals.

- Another question of ethics and morals. With the possible popularization of this technology and commercialization for civil purposes, ethical aspects should be raised, and software can not be allowed to release the execution of war goods such as knives, weapons or something of bio-construction, except for research or imminent risk of harm the health of the human being.

4.4. New Pandemic Scenario

In the time of the Covid-19 pandemic, many private and public institutions, as well as professionals or ordinary citizens saw in Additive Manufacturing a way to help with their communities, quickly developing support systems for fixing visors.

Use in hospital and personal protective equipment such as visors, very necessary in the days of Covid-19, with faster response from conception (project) to the execution of the piece itself. The entire structure of the visor, as well as the fixation, was made using AM, FDM process.

Although the manufacturing time for AM is not fast for the quality that is needed (in about 3 hours) it was an innovative action worldwide, and motivating large corporations to do the same in a scenario of complete stagnation of economic activities, because of the Covid-19 pandemic. Figure 6 shows an example of a visor manufactured by the FDM process.

(a) **(b)**

(c) **(d)**

Figure 6 – Visor made by FDM (author´s source). a, b) Visor structure, with fasteners (orange color) to the film. c) Visor. d) Visor in use.

5. Conclusions

All classes of materials known as polymers, metal, ceramics and composites can be used for manufacturing or repair of parts and components by AM technology, with specific developments of both materials and equipment.

After the consolidation of polymeric and metallic materials, the opportunities and challenges for ceramic and composite materials can be evaluated, which can occur together.

Finally, the AM technology is revolutionary and can change the actual industry, and human behaviour scenario to better, in Covid-19 times and after, with personal protective equipment goods and others.

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