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ANALYSIS OF THE CURRENT SCENARIO OF ADDITIVE MANUFACTURING STANDARDIZATION AND CERTIFICATION

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Standards are important for the industry and can be of particular interest for emerging, highly technical industries, such as the additive manufacturing (AM), because they provide foundational elements on which the industry might be focused. On the other hand, the certification of a component means defining ways to know that a part fabricated by AM will perform the same function than one manufactured using conventional technologies. Thus, the aim of this work is the analysis of the current framework to develop standards and certifications related to AM. The methodology of this study is mainly based on identifying and collecting current standards dedicated to harmonize the actual paradigm of AM implementation in this new era known as Industry 4.0. Thus, it is concluded that 55% of the new AM standards will be dedicated to the design or manufacturing in AM, as well as their related materials to process. The remaining standards are related to testing procedures, qualification and certification of parts. Focusing on the type of AM technology, 50% of newly AM standards will be related to powder bed fusion (PBF), whereas 33% will be related to extrusion-based additive manufacturing (EBAM) and the rest 17% to directed energy deposition (DED) processes.

Keywords: *additive manufacturing; standard; certification; advanced manufacturing; industry 4.0;*

ANÁLISIS DEL ESCENARIO ACTUAL DE CERTIFICACIÓN Y NORMALIZACIÓN EN FABRICACIÓN ADITIVA

La normativa es fundamental en la industria y, en especial, en industrias emergentes y altamente técnicas, como la fabricación aditiva (FA), ya que proporciona elementos fundamentales para su desarrollo. Por otro lado, la certificación de un componente permite asegurar que una pieza fabricada por FA podrá realizar la misma función que una fabricada utilizando tecnologías convencionales. El objetivo de este trabajo es el análisis del marco actual para desarrollar normas y certificaciones relacionadas con la FA. La metodología de este estudio se basa principalmente en la identificación y recopilación de las normas actuales dedicadas a armonizar la implementación de la FA en esta nueva era conocida como Industria 4.0. Se concluye que el 55% de las nuevas normas de FA estará dedicado al diseño o fabricación en FA, así como a los materiales relacionados. Las normas restantes estarán relacionadas con los procedimientos de prueba, calificación y certificación de partes. Centrándose en el tipo de tecnología de FA, el 50% de las nuevas normas estarán relacionados con la técnica de fusión de lecho en polvo, mientras que el 33% estará relacionado con la fabricación aditiva basada en extrusión y el 17% restante con los procesos de deposición dirigida de energía.

Palabras clave: *fabricación aditiva; normativa; certificación; fabricación avanzada; industria 4.0;*

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1. Introduction

Currently, the industrial value creation in the early industrialized countries is shaped by the development towards the fourth stage of industrialization, the so-called Industry 4.0. Industry 4.0 is a term applied to a group of rapid transformations in the design, manufacture, operation and service of manufacturing systems and products (Stock and Seliger, 2016; Davies, 2015).

Industry 4.0 is the next phase in the digitization of the manufacturing sector, driven by four disruptions: the great rise in data volumes, computational power, connectivity and improvements in transferring digital instructions to the physical world, such as advanced manufacturing and robotics (Baur and Wee, 2015). Particularly, advanced manufacturing relies on new technologies that enable flexibility and agility. Examples of applicable areas are bio-manufacturing, semiconductors, advanced materials, additive manufacturing, and nano-manufacturing. Advanced manufacturing -in the form of additive manufacturing, advanced materials, smart, automated machines, and other technologies- is ushering in a new age of physical production (Hagel, 2015).

Additive manufacturing (AM) comprises a suite of emerging technologies that fabricates three-dimensional objects directly from digital models through an additive process, typically by depositing successive layers of polymers, ceramics, or metals (US DOE, 2012). The additive manufacturing processes can be used to manufacture prototypes, tool and fully functional end-use parts (ISO 17296-2, 2015). Unlike traditional manufacturing processes, AM technologies bond materials together to build products. The numerous additive manufacturing processes differ according to the materials and methods of patterning and melting layers they employ (Ford, 2014).

Whereas AM processes are evolving and changing rapidly (Tamburrino et al., 2015), typical AM processes are can be now classified in the following seven categories: Vat photopolymerization, material jetting, binder jetting, powder bed fusion, material extrusion, directed energy deposition and sheet lamination (ISO 17296-2, 2015).

One important aspect of AM is that there is a very fast turnaround from concept to part, enabling faster prototyping. However, AM is still hampered by low productivity, poor quality and uncertainty in mechanical properties of final parts. The root cause of undesired effects lies in the control aspects of the process (Bikas, 2016).

AM has been witnessing tremendous growth over the past three decades, particularly in the fields of medical, aerospace, automobile, and defense industries (Zhao et al., 2017). The AM material market is expected to grow from $470M in 2013 to over $1.09B in 2022 (Forster, 2015). In 2016, 424 AM-related patents issued by the US patent office were roughly 3 times the number in 2006 and 20 times the number in 1996 (US Patent, 2017). Around 13,000 AM industrial systems were sold in 2016, approximately twice the number in 2011 (Wohlers, 2017).

Additive manufacturing is poised to bring about a revolution in the way products are designed, manufactured, and distributed to end users. Due to the rapid proliferation of a wide variety of technologies associated with AM, there is a lack of a comprehensive set of design principles, manufacturing guidelines, and standardization of best practices (Gao et al. 2015).

2. Objectives

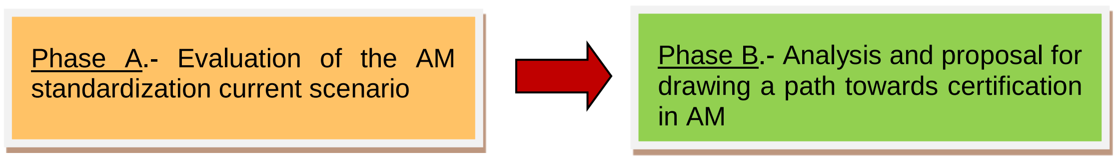
Standards can be particularly important for emerging and highly technical industries, such as AM, because they provide the foundational element on which the industry might be built. Standards are necessary to ensure that such rules of the game are established, adhered to, and respected by all stakeholders. For example, in manufacturing, standards are often essential, as they outline the parameters that must be met to deliver a quality product. Raw materials, machines, tooling, equipment operators and engineers, suppliers and the manufacturing process itself, all need standards and a mechanism for qualifying/certifying against those standards to make parts with the required quality. For example, the aircraft industry has adopted different AM components for reducing aircraft weight -including flight deck monitor arms, seat buckles, and various hinges and brackets- which can lead to greater aircraft fuel efficiency (Huang et al., 2015).

Standards can also help organizations escape the inertia of the status quo (Tilton, Dobner and Holdowsky, 2017). Thus, the aim of this work is the analysis of the current framework to develop standards and certifications in the AM industry. The methodology of this study is mainly based in identifying and collecting current standards dedicated to harmonize the actual paradigm of AM implementation.

3. Methodology

The methodology of this work consists of two main steps (Fig. 1), one dedicated to evaluate the necessity of standardization in the AM industry (phase A), and another one to analyse the crucial value of the certification to widespread the implementation of AM practices in the current manufacturing scenario (phase B shown in the "Considerations and results" section).

Figure 1: Methodology of analysis



Phase A. Evaluation of the AM standardization current scenario

Industrial application of Rapid Prototyping (RP) as a material additive manufacturing process started in 1988 (Kruth, Leu and Nakagawa, 1998); after that milestone, the development of AM techniques has evolved continuously up to present (Table 1).

Table 1. AM applications timeline (Royal academy of engineering, 2013)

Timeline	Development
1988–1994	Rapid prototyping
1994	Rapid casting
1995	Rapid tooling
2001	AM for automotive
2004	Aerospace (polymers)
2005	Medical (polymer jigs and guides)
2009	Medical implants (metals)
2011	Aerospace (metals)
2013–2016	Nano-manufacturing
2013–2032	Architecture/biomedical implants/in situ bio-manufacturing/body organs

A historic milestone was undoubtedly the launching of the first low-cost AM system in 1996 by Stratasys. This company introduced the Genisys machine, which used an extrusion process similar to FDM, but based on the technology developed at IBM's Watson Research Center. After eight years of selling stereolithography systems, 3D Systems sold its first 3D printer (Actua 2001) in 1996, using a technology that deposited wax material layer by layer using an inkjet printing mechanism. The same year, Z Corporation launched its Z402 3D printer, primarily for concept modeling. Based on MIT's inkjet printing (3DP) technology, the Z402 produced models using starch- and plaster-based powder materials and a water-based liquid binder. Also in 1996, Schroff Development began to sell its semi-automated paper lamination system for under $10,000 (Wohlers and Gornet, 2014).

Another important milestone was the advent of the RepRap project in 2005, an open source community with the goal of making 3D printing technologies accessible to all (Matias and Rao, 2005).

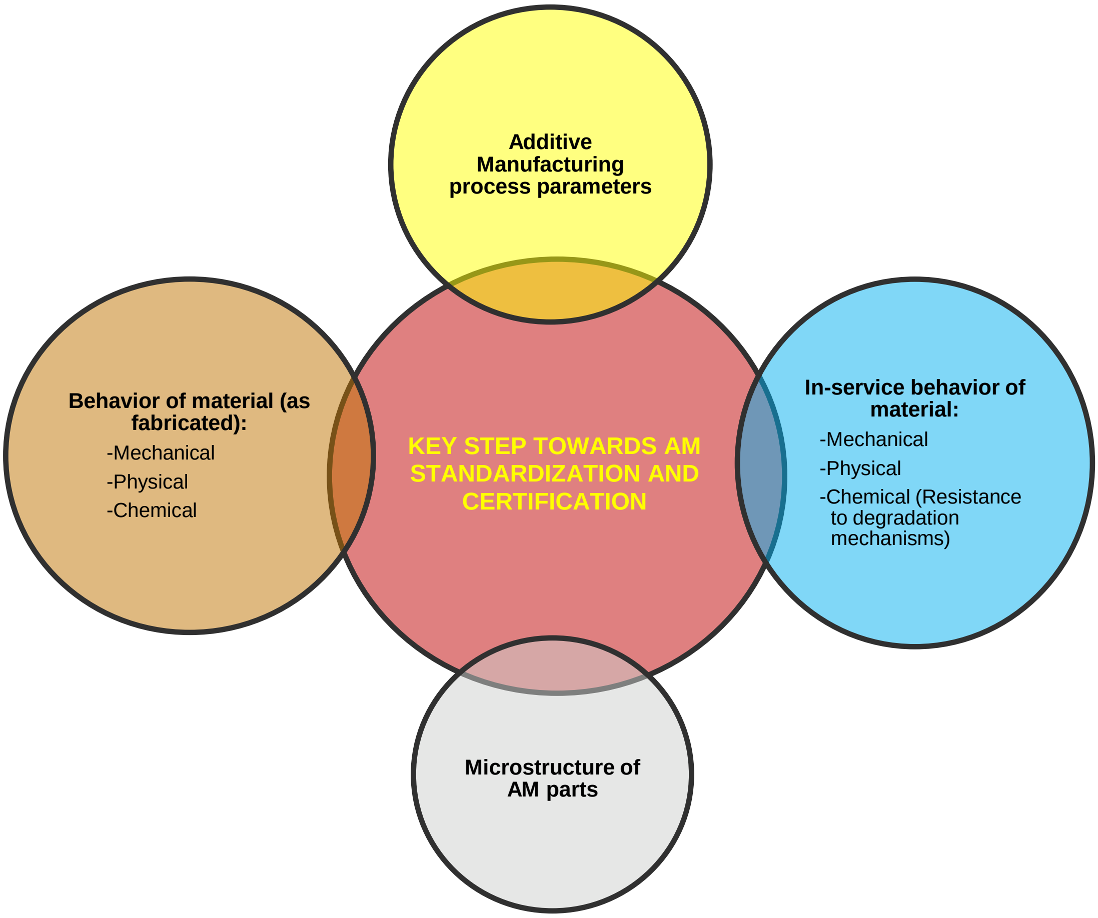
Nowadays, the highlighted advantages of additive manufacturing are very well defined. Some of them are:

- Part complexity does not impact the manufacturing process.
- Part can be considered for functionality and aesthetics.
- New designs can easily be made and costs are driven by the volume of printed material.

Certainly, the lack of AM specific mechanical standards creates challenges for stakeholders to provide equal comparisons between machines, materials, and models that predict final part properties in order to generate allowable designs. The inferior mechanical performance of current AM parts compared to the traditional manufactured parts is a risk for AM development (Forster, 2015; Stahl, 2013). In heavily regulated industries such as aerospace and medical device manufacturing, there is a need for robust process monitoring and control capabilities to be developed in order to reduce process variation and ensure quality (Spears and Scott, 2016).

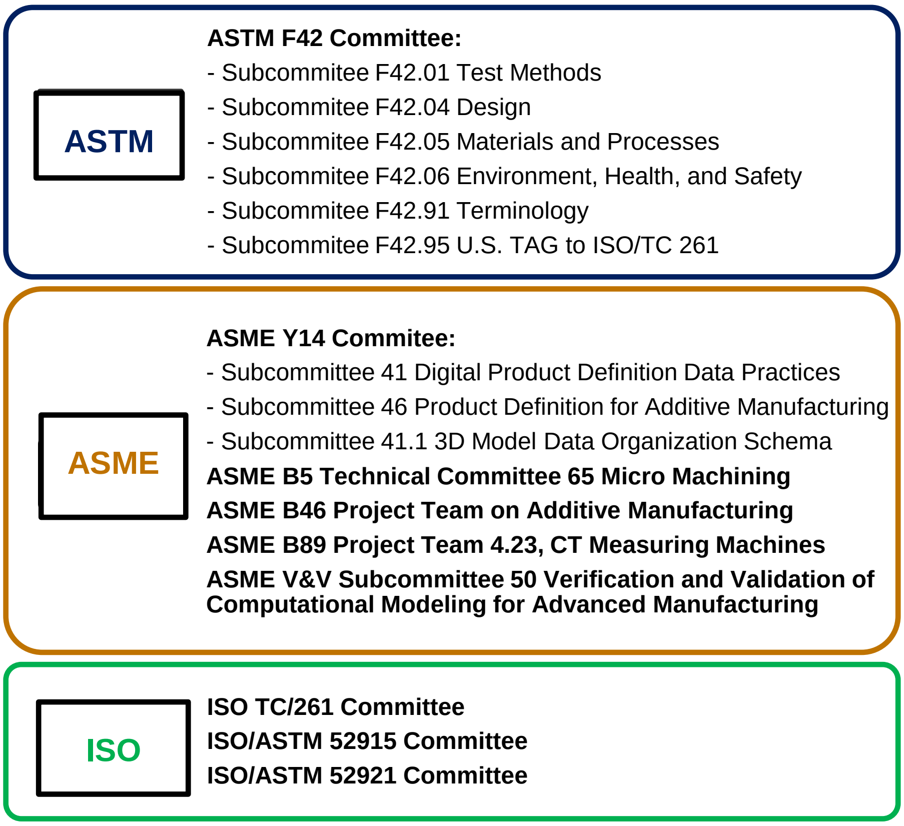
A sampling performed among recent research papers on AM showed that hardly 5% emphasize on reliability, failure or degradation of the AM parts (Yanguas-Gil, 2016). This endorses that a challenge for the AM research and development is to standardize processes, relating manufacturing process with microstructure and in service-behavior (Fig 2).

Figure 2: Relationship between AM parameters and microstructure and behaviour of parts fabricated by AM



The current initiative to harmonize the standardization framework related to AM processes is now mainly being leaded by the American Society for Testing of Materials (ASTM) F42, the American Society of Mechanical Engineers (ASME) Y14 and the International Organization for Standardization (ISO) TC/261 committees (Fig 3). Other committees involved in AM standards are the constituted by American Welding Association (AWS), the Association Connecting Electronic Industries (IPC) and the National Aeronautics and Space Administration (NASA).

Figure 3: Main AM standardization committee



The agreed-upon common structure defined by the ISO/ASTM committees consists of multiple levels and a hierarchy of AM standards, with the following three levels (ISO/TC 261 and ASTM F42 AM plan, 2013):

- General standards: standards that specify general concepts, common requirements, or are generally applicable to most types of AM materials, processes, and applications.
- Category standards: standards that specify requirements that are specific to a material or process category.
- Specialized standards: standards that specify requirements that are specific to a material, process, or application.

Table 2 shows the main published general standards. These standards deal with generic concepts related to process development, data reporting and processing and mechanical behavior characterization.

Table 2. Main ASTM and ISO general standards related to AM

General Standards
ASTM F2971 – 13. Standard practice for reporting data for test specimens prepared by additive manufacturing.
ASTM F3049-14. Standard guide for characterizing properties of metal powders used for additive manufacturing processes
ASTM F3091/F3091M-14. Standard specification for powder bed fusion of plastic materials.
ASTM F3122 – 14. Standard guide for evaluating mechanical properties of metal materials made via additive manufacturing processes.
ISO DIS 17296-1 (2014) Additive manufacturing - General principles - Part 1: Terminology.
ISO 17296-2 (2015.) Additive manufacturing - General principles -Part 2: Overview of process categories and feedstock.
ISO 17296-3 (2014). Additive manufacturing - General principles -Part 3: Overview of process categories and feedstock main characteristics and corresponding test methods.
ISO 17296-4 (2014). Additive manufacturing - General principles -Part 4: Overview of data processing.
ISO/ASTM 52915 (2016). Specification for additive manufacturing file format (AMF) Version 1.2.

Table 3 exhibits the published category and specialized standards along with the AM process technology involved and the processed materials. Thus, it can be observed that the mostly of AM published standards are dedicated to powder fusion techniques, covering metals such as stainless steel, nickel and titanium alloys, typically used in aerospace and medical application.

Table 3. Main ASTM and ISO category and specialized standards related to AM

Category standards	AM process	Material
ASTM F3184 – 16. Additive manufacturing stainless steel alloy (UNS S31603) with powder bed fusion	PBF	Stainless Steel Alloy (UNS S31603)
ASTM F2924 – 14. Standard specification for additive manufacturing Titanium-6 Aluminum-4 Vanadium with powder bed fusion.	PBF	Ti_6Al_4V
ASTM F3001 – 14. Standard specification for additive manufacturing Titanium-6 Aluminum-4 Vanadium ELI (Extra Low Interstitial) with powder bed fusion.	PBF	Ti_6Al_4V (ELI)
ASTM F3055 – 14. Standard specification for additive manufacturing nickel alloy (UNS N07718) with powder bed fusion.	PBF	Nickel alloy (UNS N07718)
ASTM F3056 – 14. Standard specification for additive manufacturing nickel alloy (UNS N06625) with powder bed fusion.	PDF	Nickel alloy (UNS N06625)
ISO/ASTM CD 52903-2. Additive manufacturing - Standard specification for material extrusion based additive manufacturing of plastic materials- Part 2: Process -- Equipment	Extrusion based AM (EBAM)	Polymers (general)

Additionally, ASTM F42 and ISO TC 261 committee is involved in the development of the following standards to provide measurement methods for the mechanical properties of additive manufactured parts:

- ASTM WK30107. Practice for reporting results of testing of specimens prepared by additive manufacturing.
- ASTM WK37654. New guide for directed energy deposition of metals
- ASTM WK40419. Test methods for performance evaluation of additive manufacturing systems through measurement of a manufactured test piece.
- ASTM WK47301. New guide for nondestructive testing of additive manufactured metal parts used in aerospace applications.
- ASTM WK48732. New specification for additive manufacturing stainless steel alloy (UNS S31603) with powder bed fusion.
- ASTM WK49229. New guide for orientation and location dependence mechanical properties for metal additive manufacturing.
- ASTM WK55297. New guide for additive manufacturing -General principles- Standard test artefacts for additive manufacturing.
- ASTM WK55610. New test methods for the characterization of powder flow properties for additive manufacturing applications.
- ASTM WK38342. New guide for design for additive manufacturing.
- ASTM WK48549. New specification for AMF support for solid modeling: Voxel information, constructive solid geometry representations and solid texturing.
- ASTM WK51282. New guide for additive manufacturing -General principles- Requirements for purchased AM parts.
- ASTM WK51329. New specification for additive manufacturing Cobalt-28 Chromium-6 Molybdenum Alloy (UNS R30075) with Powder Bed Fusion.
- ASTM WK53423. New Specification for Additive Manufacturing AlSi10Mg with Powder Bed Fusion
- ASTM WK53878. New specification for additive manufacturing -Material extrusion based additive manufacturing of plastic materials- Part 1: Feedstock materials.
- ASTM WK54856. New guide for principles of design rules in additive manufacturing.
- ISO/ASTM DIS 52901. Additive manufacturing -General principles- Requirements for purchased AM parts.
- ISO/ASTM NP 52902, Additive manufacturing -General principles- Standard test artifacts.
- ISO/ASTM DIS 52903-1. Additive manufacturing -Standard specification for material extrusion based additive manufacturing of plastic materials- Part 1: Feedstock material.
- ISO/ASTM CD 52903-2. Additive manufacturing -Standard specification for material extrusion based additive manufacturing of plastic materials- Part 2: Process equipment.
- ISO/ASTM NP 52905. Additive manufacturing -General principles- Non-destructive testing of additive manufactured products.
- ISO/ASTM DIS 52910. Standard Practice -Guide for design for additive manufacturing.
- ISO/ASTM NP TR 52912. Design of functionally graded additive manufactured parts.
- ISO/TC 44/SC 14. Welding for aerospace applications -Qualification of laser beam machines for metal powder bed additive manufacturing.

On the other hand, ASME Y14 committee is going to publish two standards related to AM:

- ASME Y14.46-201X. Product definition practices for additive manufacturing.
- Y14.41.1-201X. 3D Model organization schema practices.

In addition, the American Welding Association (AWS) D20 and IPC D64 committees are working in the development of the following standards:

- AWS D20.1. Standard for fabrication of metal components using additive manufacturing
- IPC-6902. Qualification and performance specifications for printed electronics (Additive Circuitry)

- IPC/SGIA-5222. Process guideline for screen printing for printed electronics (Additive Manufacturing)

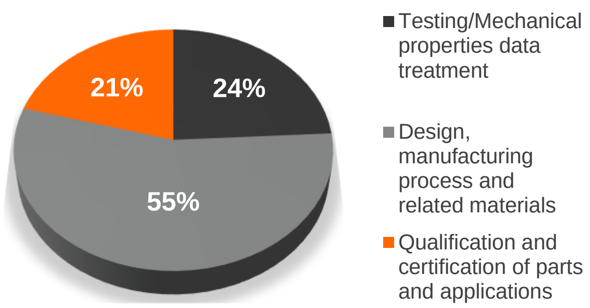
Finally, NASA Marshall Space Flight Center committee is developing the following standard:

- Draft standard for laser powder bed fusion (PBF) additive manufacturing (AM): engineering and quality standard for additively manufactured spaceflight hardware.

4. Considerations and results

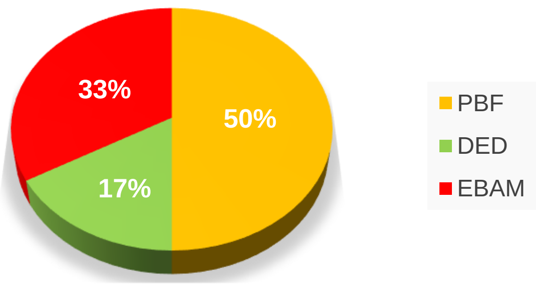
Whereas in 2015 there were 20 approved ISO and ASTM standards related with AM (Moss, 2015), as of January 2018, there are 45 standards of standards drafts related to AM (Fig .4) considering all in-progress and approved standards issued by ASTM, ISO, ASME, AWS, IPC and NASA committees. This rapid growth endorses that standardization in AM is crucial. Fig. 4 provides graphically in percentage, a breakdown of in-development AM standards by aim of the standard.

Figure 4: In-development standards. Type of standard



As Fig 4 provides, 55% of the new standards will be dedicated to the design or manufacturing in AM, as well as their related materials to process, while 24% of the standards will be dedicated to testing procedures and the evaluation of mechanical properties. The remaining standards (21%) are related to qualification and certification of parts. Focusing on the type of AM technology, Fig. 5 exhibits that the 50% of newly AM standards will be related to powder bed fusion (PBF), the 33% related to extrusion-based additive manufacturing (EBAM) and the 17% to directed energy deposition (DED) processes.

Figure 5: In-development standards related to manufacturing process and processed materials



Notes: DED process comprises 'Laser engineered net shaping, directed light fabrication, direct metal deposition and 3D laser cladding'.

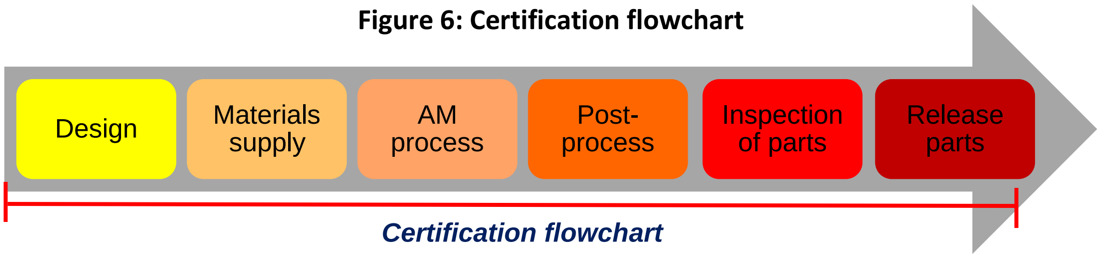
While a lack of AM standards has been detected, there are standards like ASME Y14.5 (2009) that deal with AM concepts in its section §1.1, or ASME Y14.41 (2012) that establishes requirements and references documents applicable to the preparation and revision of digital product definition data (Ameta 2015; NAMMI, 2017). Other examples of applicability of existing conventional standards to AM practice is discussed by Forster (2015) who describes the applicability of mechanical testing of polymer AM materials and parts.

Phase b. Analysis and proposal for drawing a path towards certification AM

In addition to the lack of standards for design, manufacturing and testing of AM parts, another reason that prevents the democratization of AM in the industry is the lack of certifications of AM parts that ensure the strict quality standards, safety and consistency requirements demanded by industry, and provided nowadays by the traditional manufacturing industry. Thus, several companies committed to the AM development and its overall implementation in the industry, are working closely with certification bodies to overcome the technological challenges associated with AM part certification. Some research even shows that prolonged standards competition between mutually exclusive formats may have real impact on product acceptance by the consumer (Chakravarti and Xie, 2006).

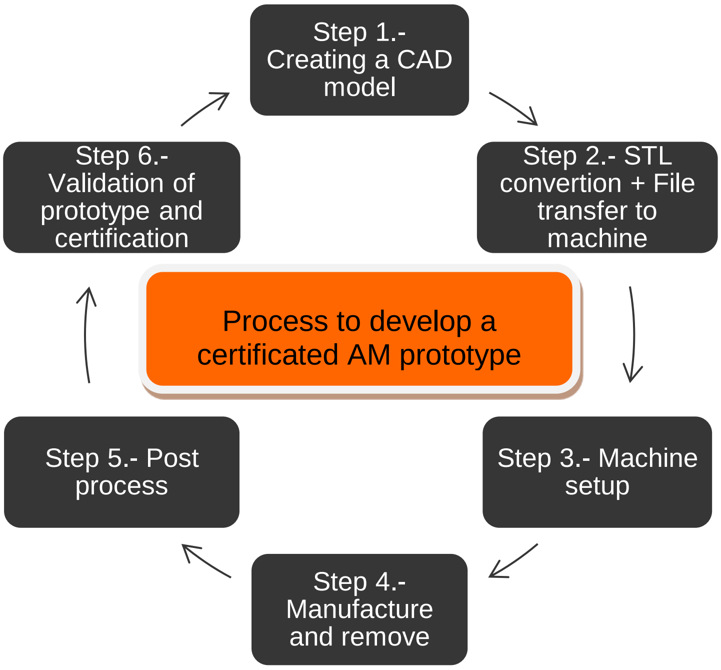
Certification of a part means defining ways to know that an AM part will perform the same function as one traditionally manufactured using subtractive manufacturing processes. Thus, additive manufacturing can be moved from prototyping into production and commercialization (Fig. 6).

Figure 6: Certification flowchart



AM involves several steps (Fig. 7) that move from the virtual CAD description to the physical resultant part (Gibson and Rosen, 2015).

Figure 7: Process to develop a certificated AM prototype



The steps involved in the manufacturing of a prototype and its certification is developed in the above mentioned steps (as provided by Fig.7) that can be grouped in the following stages:

Steps 1 to 3- Creating a CAD model, STL conversion and machine setup

All AM parts must start from a software model that fully describes the geometry (step 1). Reverse engineering equipment (e.g., laser and optical scanning) can also be used to create this representation (Gibson and Rossen, 2015). Furtherly, the CAD model is transferred into a SLT format (step 2) accepted by nearly every AM machine. This is the basis for the slice calculation. Once configured (step 3) the AM machine (material constraints, temperature, speed of injection, layer thickness, timings, etc), the part is ready to be manufactured.

Steps 4 to 5- Manufacture the part, remove from equipment and post-process

The manufacture of an AM part (step 4) is an automatically process, that hardly requires supervision. Once built, final cleaning (step 5) is necessary to be performed.

Step 6- Validation of prototype and certification

The final step (step 6) consists of validating the prototype and proceed to the certification of the part.

One of the key aspects for qualification of AM parts/components is the mechanical performance that requires a wide range of mechanical testing/characterization. The determination of materials properties of parts in the AM industry has gathered a significant amount of interest over the last 4 years (Mahesh et al., 2015; Slotwinsky et al., 2012; Slotwinsky et al., 2014). Currently, there are no consensus-based public standards in this area, except for a few examples related to terminology and data file formats (Seifi et al., 2016).

In this work, the approach is centered on the validation of prototype and certification, doing an analysis of AM standards.

The validation of prototype involves the validation of manufacturing conditions and therefore the controller program and the manufacturing scheme that provides the correct instructions to obtain the part with the quality standards required.

5. Conclusions

The lack of AM specific mechanical standards creates challenges for stakeholders to provide intercomparisons between machines, materials, and models that predict final part properties to generate valid designs. The inferior mechanical performance of current AM parts compared to the traditional manufactured parts is a risk for the AM development (Forster, 2015; Stahl, 2013).

In this work, an evaluation of the current standardization framework in the AM industry has been performed considering the recent advances of ASTM, ISO and ASME committees. In addition, an analysis of certification scenario has been carried out by presenting a proposal of certification flowchart covering different steps of the AM processes.

Once analyzed the current AM standardization scenario, it is concluded that 55% of the new AM standards will be dedicated to the design or manufacturing in AM, as well as their related materials to process, while 24% of the standards will be dedicated to testing procedures and the evaluation of mechanical properties. The remaining standards (21%) are related to qualification and certification of parts.

Focusing on the type of AM technology, 50% of newly AM standards will be related to powder bed fusion (PBF), while 33% will be related to extrusion-based additive manufacturing (EBAM) and the 17% to directed energy deposition (DED) processes.

Standardization and certification strategies must be considered necessarily to homogenize and structure manufacturing parameters and schemes, equipment controller software and post-process part testing.

In the future, this approach will be applied to develop quantitative methodologies to analyze standardized requirements of AM materials and processes.

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