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AM-motion

A STRATEGIC APPROACH TO INCREASING EUROPE'S VALUE PROPOSITION FOR ADDITIVE MANUFACTURING TECHNOLOGIES AND CAPABILITIES

Grant Agreement Nº 723560

Standardisation report: gaps and procedures

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Table of Abbreviations

3D	Three-dimensional
AENOR	Spanish Association for Standardization and Certification
AFNOR	French Association of Normalization
AFRL	Air Force Research Lab
AM	Additive Manufacturing
AMF	Additive Manufacturing File Format
AMSC	Additive Manufacturing Standards Collaborative
ANSI	American National Standards Institute
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing Materials
AWS	American Welding Society
BSI	British Standards Institution
CEN	European Committee for Standardization
CENELEC	European Committee for Electrotechnical Standardization
CMH-17	The Composites Handbook
DIN	Deutsches Institut für Normung e.V. (in English, the German Institute for Standardization)
EASA	European Aviation Safety Agency
EU	European Union
FAA	Federal Aviation Administration
FP7	7 th Framework Programme for Research and Technological Development
H2020	Horizon 2020 EU Research and Innovation Programme
IEEE	Institute for Electrical and Electronics Engineers
ISO	International Organization for Standardization
JWC	Joint Working Group
MMPDS	Metallic Materials Properties Development and Standardization
MOU	Memorandum of Understanding
NADCAP	National Aerospace and Defense Contractors Accreditation Program
NASA	National Aeronautics and Space Administration
PSDO	Partner Standards Development Organization
RTAM	Rapid Technologies and Additive Manufacturing
SDO	Standards Developing Organization
SIS	Swedish Standards Institute
SME	Society of Manufacturing Engineers
STAIR	Standardization, Innovation and Research
STL	Standard Triangle Language
TC	Technical Committee
TC	Technical Committee
UL	Underwriters Laboratories
UNI	Italian Organization for Standardization
US	United States
US DoD	United Stated Department of Defence
VDI	The Association of German Engineers
WG	Working Group
WP	Work package

1 Introduction

The present document constitutes Deliverable D3.2 in the framework of the AM-Motion project "*A strategic approach to increasing Europe's value proposition for Additive Manufacturing technologies and capabilities*" (Project Acronym: AM-motion; Contract No.: 723560). This document is the result of the activities performed within task T3.2 "*Standardisation framework and process*", within the framework of work package 3 (WP3), titled "*Analysis of Non Technological Aspects*".

Additive manufacturing (AM), also known as 3D printing, proliferated years ago because its usefulness in building prototypes with only a few number of early applications in production of end products like hearing aids and hip implants. Nowadays, additive manufacturing finds industrial applications in several sectors, thanks to its potential for producing customized or improved performance products derived from a high degree of design freedom that cannot be achieved by the subtractive technologies, for saving costs or for shortening the supply chain by on-site manufacturing. According to Wohler's report,[1] the size of AM worldwide market in 2016 was estimated at a value of $6.023 billion. The use of AM for the production of parts for final products has experienced significant growth in the last seven years. In fact, the market has grown by nearly 5.7 times over this period. AM expansion has been particularly relevant in the aerospace and the medical industry. It is remarkable that these sectors require high reliability and are highly regulated and sensitive-process ones, where the qualification of new processes and materials as well as the certification of new designs can be time consuming, complex, and expensive.

Additive manufacturing technology standards are designed to ensure products, services and systems are safe, reliable and consistent. They are intended to promote knowledge of the industry, help stimulate research and encourage the implementation of the technology. Standards are reference documents that represent a consensus among the players and that define voluntary characteristics and rules in a specific industry. The concrete benchmarks they define are based on the field's collective knowledge, which can then be distilled and updated. In that way, standardization is a key enabler for the large-scale introduction of any technology. Regarding AM technologies, standardized practices are particularly important because:

- Standardized practices create conformity amongst the different organizations and industries that use the technology. AM encompasses many processes and materials, and the range of additive processes and materials can be confusing. Many of the system manufacturers have created unique process names and materials designations to differentiate themselves from their competitors, but many of the different systems actually employ similar processes and materials. Fortunately, a standard system already exists for grouping AM processes and materials and for categorizing them into families.
- AM differs from traditional manufacturing since it is much less time- and labour-intensive by eliminating the need for tool production. This is possible because the parts are

[1] Wohlers Report 2017. 3D printing and additive manufacturing state of the industry. Annual worldwide progress report. Wohlers Associates.

manufactured directly from a digital file. STL, still the most applied “quasi-standard”[2] data format used in AM in the last three decades is a good example of a standard that has greatly helped the development of the technology by providing an open and practical data exchange format for model data. The new AMF file, which was introduced as official standard in 2011, was developed to better meets the current needs of additive manufacturing technology without the limitations of STL.

- Parts produced by these technologies have properties that can be quite different from conventional wrought or cast metals. AM is a sensitive process in which every “pixel” of the part is produced individually and where many parameters can influence the quality. This has proven to be a barrier to widespread qualification of the technology in critical applications. The development of standards helps to address this issue.
- AM is capable of creating high-quality parts, but the technology and its application have not matured to the point of guaranteeing quality over a prolonged production run. A lack of process monitoring and control are partly the cause, and quality standards for materials, processes and part testing can be the solution.

In parallel towards the moving to industrial production, some standards in the field of additive manufacturing have been created, concerning their processes, terms and definitions, process chains (hard- and software), test procedures, quality parameters, supply agreements and all kind of fundamentals. Others are still under development or in the ballot and publication process within international standard bodies. This deliverable aims to analyse the current AM standardization framework to identify the gaps and existing barriers in general and specifically for particular sectors.

2 Standardization framework

2.1 Standards developing organizations

Standardization is performed in committees and working groups within the Standards Developing Organizations (SDOs) by consensus building of all participating delegates and experts. Contributions are based on an interest in developing the standards, as no funding or compensation is provided from SDOs.

At international level, there are three main SDOs whose Technical Committees deal with AM standardisation issues:

- ISO is the international global standardization organization. **ISO Technical Committee 261 on Additive Manufacturing** (**ISO/TC 261)** was formed in 2011 after a standardization initiative from DIN, based on VDI Guidelines on “rapid technologies”. Its scope is the “standardization in the field of AM concerning their processes, terms and definitions, process chains (hard- and software), test procedures, quality parameters, supply

[2] The STL format was launched by 3D systems, but there is no official standard created.

agreements and all kind of fundamentals".[3]

Membership is based on representation of different national standardization organization, and each member organization may nominate experts for different workgroups. Current membership consists of 22 participating countries and 8 observing organizations (Figure 1).

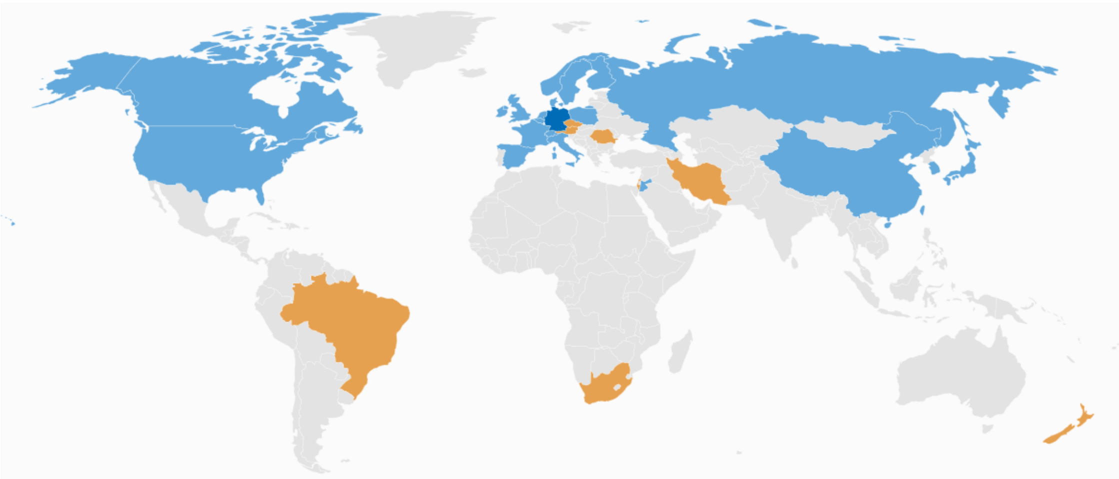

Figure 1. *Map of ISO/TC 261 national participating (blue colour) and observing members (brown colour). Source: ISO webpage*

ISO/TC 261 is organized in five working groups:

- WG1 on Terminology, coordinated by Sweden.
- WG2 on Methods, Processes and Materials, coordinated by Germany.
- WG3 on Test Methods, coordinated by France.
- WG4 on Data Transfer and Design, coordinated by the UK.
- WG6 on Environment, health and safety, coordinated by Canada.

ISO/TC 261 has also Joint Working Groups with other committees in ISO such as "ISO/TC 261/JWG 5" with TC44 for aerospace applications (Joint ISO/TC 261 - ISO/TC 44/SC 14 WG: Additive manufacturing in aerospace applications). Moreover, ISO/TC 261 has liaison agreements through it exchanges information with other ISO committees. Working groups and Liaison Committees of ISO/TC 261 are collected in Annex 1.

- ASTM (American Society for Testing Materials) International is a globally recognized leader in the development and delivery of voluntary consensus standards. **ASTM International Committee F42 on Additive Manufacturing Technologies** was organized by industry in 2009 with the aim of developing consensus standards that will support the adoption of AM across multiple industrial sectors.

[3] Scope from ISO web page on December 2017. A modified scope was balloted at the plenary meeting in Stockholm on September 2017, but it has not yet been published.

Membership is based on representation of different stakeholders (companies, universities, research organizations, etc.). Participation in F42 does not require membership, but voting rights do require it. F42 current membership is of 550+ individual members from more than 26 countries.

The committee is further divided in the following subcommittees and sub-subcommittees:

- F42.01 Test Methods.
- F42.04 Design.
- F42.05 Materials and processes.
    - F42.05.01 Metals
    - F42.05.02. Polymers
    - F42.05.03 Medical applications
    - F42.05.04 Aerospace applications
- F42.06 Environmental Health and Safety.
- F42.90 Executive.
    - F42.90.01 Strategic planning
    - F42.90.02 Awards
    - F42.90.05 Research and innovation
- F42.91 Terminology.

- F.42.95 US TAG to ISO TC 261. The TAG develops the official U.S. response to any standards balloted within ISO/TC 261. This coordination helps the two organizations ensure that their standards activities are compatible and complementary (see also section 2.2).

- At European level, the officially recognized European Standardization Organizations are **CEN (European Committee for Standardization) and CENELEC (European Committee for Electrotechnical Standardization)**[4] non-profit organizations. CEN, CENELEC and their national members and committees work jointly to develop and define standards that are considered necessary by market actors and/or to support the implementation of European legislation. After the publication of a European Standard, each national standards body or committee is obliged to withdraw any national standard that conflicts with the new European Standard. Hence, one European Standard becomes the national standard in all the member countries of CEN and/or CENELEC.

  Several CEN members participated in the FP7 European project SASAM[5] (Support Action for Standardization in Additive Manufacturing), which was supported by the European

[4] https://www.cencenelec.eu/Pages/default.aspx

[5] SASAM FP7 Project

Union. The project ended in February 2014, and resulted in the delivery of a Standardization Roadmap for Additive Manufacturing. The CEN-CENELEC Working Group STAIR (Standardization, Innovation and Research) together with the project SASAM decided to create the STAIR Additive Manufacturing Platform. A primary topic for discussions within STAIR-AM was the potential/possible need for a European CEN/TC on AM. Since this eventually was decided and the **CEN Technical Committee on Additive Manufacturing (CEN/TC 438)** was founded in 2015, STAIR-AM was disbanded. The actual work on European AM standards was taken over by CEN/TC438 (currently formed by 33 national member bodies). Other more general discussions and activities connected to AM standards was taken over by the AM-Platform.

2.2 Cooperative relationships

Worldwide cooperation is an important factor in developing standards for AM in an effective way. Prior to any form of collaboration, standards for AM came from independent works of different standardization bodies, resulting in duplicated efforts and standards. To rectify this situation, the pioneering collaboration for joint standards development between the ASTM F42 and ISO/TC 261 committees on AM is especially relevant.

ASTM F42 and ISO/TC 261 signed the **Partner Standards Development Organization (PSDO)** cooperation agreement in October 2011 (just few months after the creation of the ISO/TC 261 committee), with the aim of jointly develop international standards that serve the global marketplace in the field of additive manufacturing. The agreement specifies development approaches, as well as publication, copyright and commercial arrangements. Through this agreement, joint standards can be created where none has existed. Also part of the partnership is fast-tracking the adoption process of an ASTM International standard as an ISO final draft standard, formal adoption of a published ISO standard by ASTM International, and maintenance of published standards.

By summer 2013, a meeting was held to outline the structure for the development of joint ISO/ASTM standards, and the following agreements have been reached on the guiding principles to be followed and pursued by both organizations regarding the development of standards:

- One set of AM standards to be used all over the world.
- Common roadmap and organizational structure for AM standards.
- Use and build upon existing standards, modified for AM when necessary.
- Emphasis on joint standards development.
- For efficiency and effectiveness, ISO/TC 261 and ASTM F42 should begin the work together and therefore in the same direction. Specifically, in the framework of the joint plan for AM standards development, it was agreed that if one organization starts to work on a new work item, it will invite the other organization to form a Joint Group. Only if the other organization is not interested, the standard will be developed “alone”. Moreover, regular ISO/TC 261 plenary meetings are held in parallel with ASTM F42 main committee meetings.

Furthermore, in July 2016, ASTM F42 and ISO/TC 261 committees have jointly updated and approved a **common organizational structure for AM standards** that addresses the perspectives and requirements from both ISO/TC 261 and ASTM F42 (figure 2). The intention of this revised structure is to facilitate the development of modularized standards and to reduce the risk for duplication of work, as well as the risk of contradiction between standards. The structure sets three levels on which experts can develop industry standards:

- General standards (e.g. concepts, common requirements and guides, safety).
- Standards for broad category of materials (e.g. metal powders) or processes (e.g. powder bed fusion).
- Specialized standards for a specific material (e.g. Aluminum alloy powders), process (e.g. material extrusion with ABS) or application (e.g. aerospace, medical, automotive).

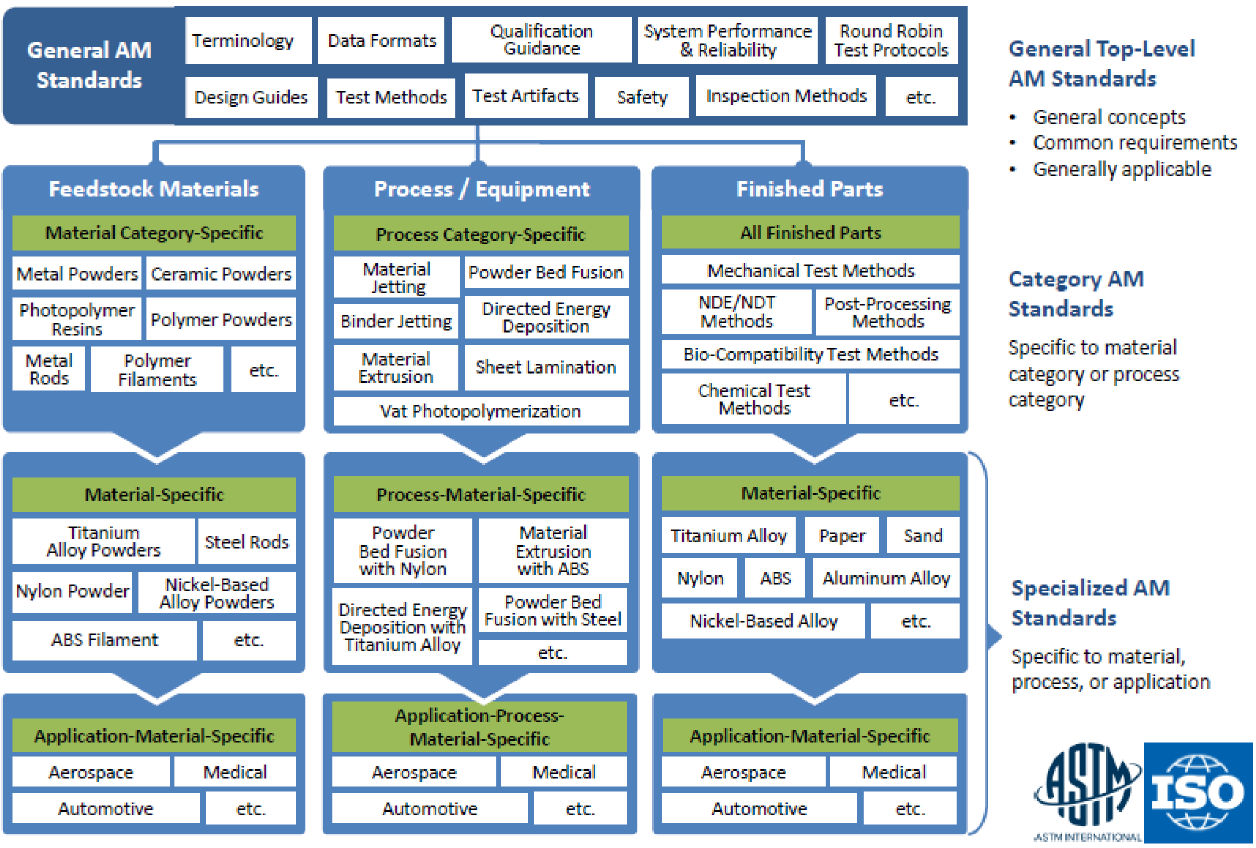

Figure 2. *Common ISO/ASTM structure of AM standards*

On the other hand, CEN has an agreement for technical cooperation with the ISO organization. Thus, the Vienna Agreement was signed in 1991 with the aim of preventing duplication of effort and reducing time when preparing standards. Specifically, an external **liaison was established between CEN/TC 438 and ISO/TC 261 on additive manufacturing**. Moreover, following the Vienna Agreement, CEN/TC 438 has adopted several ISO and ISO/ASTM standards that have now become European AM standards (EN ISO ASTM) and will replace any national standards that may exist for these topics.

Apart from the cooperative relationships described above between the ISO, ASTM and CEN AM committees, these SDOs have fostered the following relations with other relevant organizations/initiatives towards the global cooperation on AM standardization:

- **America Makes** - a U.S.-based innovation institute under Manufacturing USA and the national accelerator for additive manufacturing and 3D printing - **and ASTM International signed a memorandum of understanding (MOU) in October 2013**. The partnership further solidified in 2017 when ASTM joined America Makes as a Silver Member. The work is building more and stronger connections between researchers and the standards community, with the goal of developing standards in tandem with the introduction of new AM technologies and innovations. Key to this is the role of ASTM as it fills gaps identified by the Standardization Roadmap for Additive Manufacturing, developed by the Additive Manufacturing Standards Collaborative, where ASTM has a leadership role.
- **MOU signed in 2009 between ASTM and Society of Manufacturing Engineers (SME)**, establishing ASTM as the home for AM standards activities. The agreement also facilitates the participation of SME's Rapid Technologies and Additive Manufacturing (RTAM) community in the standards development process. SME's RTAM group is the world's largest community of technical experts focused around these advanced technologies.
- **ASTM and the 3MF Consortium** signed a **liaison agreement** on June 2016 to explore ways to collaborate and align standards and roadmaps to advance additive manufacturing innovation and deliver state-of-the-art 3D printing technologies to the market. 3MF is an industry association created to develop and promote a new full-fidelity file format for 3D printing. The 3MF Consortium was formed to close the gap between the capabilities of modern 3D printers and outdated file formats.
- **Federal Aviation Administration (FAA) and European Aviation Safety Agency (EASA)** both separately holding workshops for additive manufacturing to accelerate qualification and certification (Q&C) of the technology. Since 2015 FAA in conjunction with AFRL (Air Force Research Lab) hold three workshops to bring aerospace community together in order to discuss the status of Q&C. EASA similarly have hosted two workshops so far in 2016 and 2017 to capture European activities. Standard organizations such as ASTM International have been invited to provide status update on the standardization activities and the feedback from the community directly goes to the future activities.
- **ASTM/ISO** maintain **formal discussions** with other standardization initiatives such as the ones from **American Welding Society (AWS)**, **Institute for Electrical and Electronics Engineers (IEEE)**, **SAE International,** among others, regarding the coordination of standards development. More details about the AM standardization activities of these organizations are described in section 2.3.
- **CEN/TC 438** has established **links** with the **European AM-Platform**, the **European Welding Federation**, and the H2020 European FoFAM project. Closer collaboration was agreed with **ASD-STAN**, the European standardization body for aerospace.

2.3 Other standardization initiatives

In addition to ISO, ASTM and CEN described in section 2.1, there are other relevant initiatives in developing standards or fostering standardization for AM, which are presented in this section:

- In Europe, there are several **initiatives and national standardization committees on additive manufacturing**:
  - AFNOR in France with its committee UNM 920 Fabrication additive.
  - VDI in Germany with the GPL Committee on Production and logistics and, especially, its Committee 105 Additive Manufacturing, as well as the DIN with its NA 131-02-06 AA subcommittee Additive manufacturing in aerospace industry.
  - AENOR in Spain with the committee AEN/CTN 116 including AM.
  - SIS in Sweden with the committee SIS/TK 563.
  - BSI in UK with the committee AMT/8.
  - UNI in Italy with the committee UNI/CT 529.

  National certification bodies develop their own standards, but as these initiatives are collaborating at international level with ISO, CEN or ASTM, these efforts are used as input for the international organizations.

- Asia has also shown interest, and **China, Japan, Korea and Singapore have established mirror committees that align to ISO/TC 261**.

- America Makes, the US Additive Manufacturing Innovation Institute, partnered with the American National Standards Institute (ANSI), launched the **Additive Manufacturing Standards Collaborative (AMSC)** in March 2016. AMSC is not developing standards or specifications, but is a cross-sector coordinating body whose purpose is to help to coordinate the development of industry-wide additive manufacturing standards and specifications.

  In February 2017, the AMSC published a standardization roadmap for additive manufacturing. The roadmap identifies existing (as well as those in development) standards and specifications, assesses gaps, and makes recommendations for priority areas where there is perceived need for additional standardization. The AMSC also published the AMSC Standards Landscape. The second phase of this collaboration was kicked off in September 2017.[6] Its major goals include expanding the discussion of standards needs for polymers and other materials besides metals and engaging experts from other industry sectors such as automotive, heavy equipment, energy, consumer products, and tooling.

- The **American Society of Mechanical Engineers (ASME)** has formed some committees to address additive manufacturing standardization: ASME Y14 Subcommittee 46 Product Definition for Additive Manufacturing, ASME Y14 Subcommittee 41.1 on 3D Model Data

[6] America Makes&ANSI 2 Kick-off Meeting for Additive Manufacturing Standardization Collaborative

Organization Schema, ASME Y14 Subcommittee 48 on Direction and Load Indicator Requirement and ASME V&V Subcommittee 50, Verification and Validation of Computational Modeling for Advanced Manufacturing. Other subcommittees such as committee on Advanced Monitoring, Diagnostic, and Prognostic Technologies for Manufacturing are under development.

- The **American Welding Society (AWS)**¡Error! Marcador no definido. formed the D20 committee on additive manufacturing in 2013 to develop a standard that would integrate requirements for the additive manufacturing of metal components. The AWS D20 committee, which consists of volunteers working in various AM-related fields, is in the process of completing a draft of the AWS D20.1 standard "Specification for Fabrication of Metal Components using Additive Manufacturing". AWS D20.1 will be a comprehensive document that identifies requirements related to AM component design, procedure qualification, machine operator performance qualification, fabrication, and inspection. The scope of the draft AWS D20.1 standard includes both powder bed fusion and directed energy deposition metal AM processes.
- The **Institute for Electrical and Electronics Engineers (IEEE)**,¡Error! Marcador no definido. with an active portfolio of nearly 1,300 standards and projects under development, is a leading developer of industry standards. IEE is working in several projects related to additive manufacturing to develop the necessary standards and regulations that could lead to increased adoption of 3D printing. The Institute has already published the first part of a multi-part standard regarding 3D medical modelling, visualization, data management, simulation and printing. The published standard (IEE P3333.2.1) includes volume rendering and surface rendering techniques for 3D reconstruction from two-dimensional medical images. It also contains a texturing method of 3D medical data for the realistic visualization. Other AM standards such as "Standard for Consumer 3D Printing: Overview and Architecture" or "Standard for Test Access Architecture for Three-Dimensional Stacked Integrated Circuits" are under development.
- **SAE International**¡Error! Marcador no definido. is the world's largest aerospace consensus standards developing organization. SAE AMS AM, Additive Manufacturing, is a technical committee created in 2015 in SAE's Aerospace Materials Systems Group with the responsibility to develop and maintain aerospace material and process specifications and other SAE technical reports for additive manufacturing, including precursor materials, additive processes, system requirements and post-build materials, pre-processing and post-processing, nondestructive testing, and quality assurance. Recognizing the contributions of other standards development organizations and related bodies, the committee collaborate with organizations such as MMPDS, ASTM Committee F42 on Additive Manufacturing Technologies, AWS D20, NADCAP Welding Task Group, America Makes, CMH-17, and regulatory authorities such as FAA, EASA, US DoD, and NASA. Examples of standards development/revision activities are: "AMS7003 - Laser Powder Bed Fusion Process", "AMS7002 - Process Requirements for Production of Ni-base 625 for Production of Aerospace parts via Laser Powder Bed Additive Manufacturing", "AMS7001 - Ni Base 625 Super Alloy Powder for use in Laser Powder Bed Add Mfg machines", "AMS7000 - Additive Manufacture of Aerospace parts from Ni-base Super alloy 625 via the

Laser Powder Bed Process".

- **ASD-STAN**, the European standardization body for aerospace.¡Error! Marcador no definido. ASD-STAN publishes and sells online its own standards-library documents and is a distributor for the independently produced SAE ITC E&A (former ASD standards) standards and ASD-STAN related DIN EN standards. Over the years, ASD-STAN has established a lean and streamlined standardisation process for European aerospace standards in agreement with the European Committee for Standardization (CEN).
- **UL (Underwriters Laboratories)** is an American safety consulting and certification company headquartered in Northbrook, Illinois. It maintains offices in 46 countries. Established in 1894 as the Underwriters' Electrical Bureau (a bureau of the National Board of Fire Underwriters), it was known throughout the 20th century as Underwriters Laboratories and participated in the safety analysis of many of that century's new technologies, most notably the public adoption of electricity and the drafting of safety standards for electrical devices and components.

  Regarding additive manufacturing, the UL recently published the "UL 3400 - Outline for Investigation Additive Manufacturing Facility Safety Management." UL also offers the service Plastics for Additive Manufacturing Program (Blue Card Program), that enables customers to have published data that facilitates pre-selection of 3D printed materials and components for use in various end products. It defines the requirements necessary to recognize plastics intended for 3D printing, proving the safety, integrity and usefulness of materials. The UL Blue Card helps ensure that the component or end-product manufacturer is using a tested and certified material, as well as being monitored at regular intervals by an independent test laboratory.
- Regarding **industry**, most of the companies contribute to AM standardization by bringing their technical expertise, through delegating experts to committees and working groups at national and international level. However, there are sectors, like the **aerospace** one, where quality, reliability and safety are critical values. Therefore, aerospace companies combine international standardization with the developing of internal standards. For example, in the case of Airbus, the company works on the developing of a full set of internal standards covering the complete additive manufacturing technology introduction in the portfolio of the company (Table 1).

  Also on a national level, there are special aerospace activities ongoing as, for example, in Germany the DIN - Aerospace Standards Committee (NL) that is responsible for national standards, and represents the German standardization interests at European (CEN) and international (ISO) levels in the fields of e.g. materials. Its subcommittee NA 131-02-06 AA Additive manufacturing in aerospace industry has recently published its "DIN 65122 standard: Aerospace series - Powder for additive manufacturing with powder bed process - Technical delivery specification". In addition, the VDI subcommittee FA 105.2 published a draft guideline for the "Characterization of powder raw material" for beam melting of metallic parts.

Table 1. *The case of Airbus - An example for the aerospace sector*

<table>
<tr><th colspan="2">Internal standardization process</th></tr>
<tr><td colspan="2">Airbus's standards initially will be only internally available, but will be discussed and agreed with existing Aeronautical Authorities (i.e. EASA and FAA) within the usual certification processes dedicated to the validation and qualification of new technologies. At a second stage, it is also foreseen that those internal standards will be also available for the selected supply chain and extended enterprise partners of Airbus.</td></tr>
<tr><th colspan="2">Internal and international standardization alignment</th></tr>
<tr><td colspan="2">Internal and international standardization alignment is key for Airbus in order to facilitate a wide spread of the AM technology across the global industrial network with the effect of an increasing competition amongst potential partners. The company participates in SAE as voting member for Additive Layer Manufacturing, aiming to accelerate the availability of international standards for the ALM technologies designated as the most promising ones for Airbus applications (AMS7000, AMS7001, AMS7002, AMS7003 and AMS7004). Airbus also planned to continue working within the SAE in the standardization of already internally deployed technologies as Titanium Powder Bed and Ultem 9085.</td></tr>
<tr><th>Powder bed fusion by laser beam - Titanium</th><th>Fused deposition modelling – PEI "Ultem"</th></tr>
<tr><td>
</td><td>
</td></tr>
</table>

- On the other hand, **European projects** represent another valuable instrument to foster standardization activities. Normally it takes several years to create a standard, so its development should start already several years before the industry is demanding them. Hence, the push from the Joint Research Centre of the European Commission is to stimulate standard development already in the research phases. It is recommended that all research projects should pay attention to standardization in some way.[7]

***Table** 2* collects a list of relevant AM key EU funded projects under the FP7 and H2020

[7] "How will standards facilitate new production systems for EU innovation and competitiveness in 2025", JRC Foresight Study, 2014

programs that have addressed standardization as a primary or secondary issue.

Table 2. *EU projects with activity on AM standardization. Source: AM-motion AM e-database*

PROJECT TITLE	ACRONYM	PROJECT LEADER
A productive, afforable and reliable solution for large scale manufacturing of metallic components by combining laser-based AD	PARADDISE	FUNDACIÓN TECNALIA RESEARCH AND INNOVATION
Additive manufacturing aiming towards zero waste and efficient production of high-tech metal products	AMAZE	MTC CENTRE
Advanced digital technologies and virtual engineering for mini-factories	ADDFACTOR	SYNESIS
All-in-one manufacturing platform for system in package and micromechatronic systems	NEXTFACTORY	FRAUNHOFER IPA
An integrated business model for customer driven custom product supply chain	IBUS	TECHNOLOGICAL INSTITUTE FOR CHILDREN PRODUCTS AND LEISURE
Biomaterials and additive manufacturing: osteochondral scaffold innovation applied to osteoarthritis	BAMOS	UNIV. LAS PALMAS GRAN CANARIA
Computer aided technologies for additive manufacturing	CAXMAN	SINTEF
Developing a novel hybrid am approach which will offer unrivalled flexibility, part quality and productivity	OPENHYBRID	MTC CENTRE
Engineering compass	ENCOMPASS	MTC CENTRE
Flexible and on-demand manufacturing of customised spectacles by close-to-optician production clusters	OPTICIAN2020	ASCAMM PRIVATE FOUNDATION
Flexible mini-factory for local and customized production in a container	CASSAMOBILE	FRAUNHOFER IPA
High precision micro production technologies	HI-MICRO	KU LEUVEN
Hybrid automated machine integrating concurrent manufacturing processes	KRAKEN	FUNDACION AITIIP
Increasing resource efficieny through implementation of ALM technology and bionic design in all stages of an aircraft life cycle	BIONICAIRCRAFT	LASER ZENTRUM HANNOVER E.V
Industrial and regional valorization of FoF additive manufacturing projects	FOFAM	FUNDACION PRODINTEC
Large additive subtractive integrated modular machine	LASIMM	EUROPEAN FEDERATION FOR WELDING JOINING AND CUTTING
Modular laser-based additive manufacturing platform for large scale industrial applications	MAESTRO	CENTRE TECHNIQUE INDUSTRIEL DE LA PLASTURGIE ET DES COMPOSITES
Resource efficient production route for rare earth magnets	REPROMAG	OBE OHNMACHT AND BAUMGARTNER GMBH AND CO KG
Selective tape-laying for cost effective manufacturing of optimised multi-material components	STELLAR	NETCOMPOSITES LTD.
Support action for standardisation in additive manufacturing	SASAM	TNO
The 3A energy class flexible machine for the new additive and subtractive manufacturing on next generation of complex 3D metal	BOREALIS	PRIMA INDUSTRIE SPA
Manufacturing decision and supply chain management system for additive manufacturing	MANSYS	TWI LIMITED

3 Review on existing international standards for AM

The following table collects an overview of current standards relevant to AM and their status (published or under development), following the common 3-level ISO/ASTM structure. Proposed new standards have been also reviewed. In this sense, it should be mentioned that 15 newly-proposed standards from ASTM International Committee F42 regarding metal powder bed fusion (highlighted with an asterisk in Table 3) will help companies comply with a new checklist for accreditation by the National Aerospace and Defence Contractors Accreditation Program (NADCAP). The checklist is available through the Performance Review Institute.

Table 3. *Overview of current standards and their status (July 2017)[8]*

Category General Standards (general concepts, common requirements, generally applicable)

Sub-category	Title	Published	On-going	Proposed new standard
Terminology	ISO/ASTM 52900:2015 General principles. Standard terminology for additive manufacturing technologies	x		
	ISO/ASTM 52921:2013 Standard terminology for additive manufacturing – Coordinate systems and test methodologies	x		
	ISO 17296-2:2015 General Principles. Part 2: Overview of process categories and feedstock	x		
System performance& Reliability	ISO/ASTM 52901:2017 General Principles. Requirements for purchased AM parts	x		
	WK58234 Additive Manufacturing - Storage of Technical Build Cycle Data *			x
	ISO 17296-4:2014 General principles. Part 4: Overview of data processing	x		
	WK55610 The characterization of powder flow properties for additive manufacturing applications			x
Safety	WK59813 Hazard Risk Ranking and Safety Defense			x
Design Guides	ISO/ASTM 52910 Guide for Design for Additive Manufacturing	x		
	ISO/ASTM 52910.2 Guidelines for additive manufacturing design		x	
Data Formats	ISO/ASTM 52915:2016 Standard Specification for Additive Manufacturing File Format (AMF) Version 1.2	x		
	WK48549 New specificationfor AMF support for solid modeling: voxel information, constructive solid geometry representations and solid texturing			x
Test Methods	ASTM F2971-13 Standard practice for reporting data for test specimens prepared by additive manufacturing	x		
	ISO 17296-3: 2014 General Principles. Part 3: Main characteristics and corresponding test methods	x		
	ISO/ASTM NP 52905 Additive manufacturing -- General principles -- Non-destructive testing of additive manufactured products		x	
Test artefacts	ISO/ASTM NP 52902 Additive manufacturing-General Principles-Standard test artifacts		x	

[8] Updated list of standards can be consulted at ASTM and ISO web pages: https://www.iso.org/committee/629086.html; https://www.astm.org/COMMITTEE/F42.htm

Category AM Standards (specific to material category or process category)

Sub-category	Title	Published	On-going	Proposed new standard
Feedstock Materials	ASTM F3049-14 Standard guide for characterizing properties of metal powders used for additive manufacturing processes	x		
	ISO/ASTM DIS 52903-1 Additive manufacturing -- Standard specification for material extrusion based additive manufacturing of plastic materials -- Part 1: Feedstock materials		x	
	ISO/ASTM AWI 52907 Additive manufacturing -- Technical specifications on metal powders		x	
	WK53878 Additive Manufacturing - Material Extrusion Based Additive Manufacturing of Plastic Materials Part 1: Feedstock materials			x
	WK58219 Additive Manufacturing - Creating Feedstock Specifications for Metal Powder Bed Fusion *			x
	WK58221 Additive manufacturing - Receiving and storing of metal powders used in powder bed fusion *			x
	WK58222 Additive Manufacturing - Metal Powder Reuse in the Powder Bed Fusion Process *			x
	WK58224 Additive Manufacturing - Disposal of Metal Powders Used for Powder Bed Fusion *			x
Process/ Equipment	ASTM F3091/ F3091M-14 Standard specification for powder bed fusion of plastic materials	x		
	ASTM F3187-16 Standard guide for directed energy deposition of metals	x		
	ISO/ASTM CD 52903-2 Additive manufacturing -- Standard specification for material extrusion based additive manufacturing of plastic materials -- Part 2: Process -- Equipment		x	
	ISO/ASTM CD 52911-1 Additive manufacturing -- Technical design guideline for powder bed fusion Part 1: Laser-based powder bed fusion of metals		x	
	ISO/ASTM CD 52911-2 Additive manufacturing -- Technical design guideline for powder bed fusion Part 2: Laser-based powder bed fusion of polymers		x	
	WK58220 Additive Manufacturing - Specifying Gases and Nitrogen Generators Used with Metal Powder Bed Fusion Machines *			
	WK58223 Additive Manufacturing - Cleaning Metal Powder Bed Fusion Machines *			x
	WK58225 Additive Manufacturing - Facility Requirements for Metal Powder Bed Fusion *			x
	WK58226 Additive Manufacturing - Initial Qualification, Operational Qualification and Part Qualification of Metal Powder Bed Fusion Machines *			x
	WK58227 Additive Manufacturing - Digital Workflow Control for the Metal Powder Bed Fusion Process *			x
	WK58228 Additive Manufacturing - Establishing Manufacturing Plan and Sequence of Operation Work Flow for Metal Powder Bed Fusion Part Production *			x
	WK58230 Additive Manufacturing - Establishing a Personnel Training Program for Metal Powder Bed Fusion Part Production *			x
	WK58231 Additive Manufacturing - Creating Maintenance Schedules and Maintaining Metal Powder Bed Fusion Machines *			x
	WK58232 Additive Manufacturing - Calibration of Metal Powder Bed Fusion Machines and Subsystems *			x

Category Specialized AM Standards (specific to material, process or application)

Sub-category	Title	Published	On-going	Proposed new standard
Finished parts	WK58233 Additive Manufacturing - Post Thermal Processing of Metal Powder Bed Fusion Parts *			x
	ASTM F3122-14 Standard guide for evaluating mechanical properties of metal materials made via additive manufacturing processes	x		
	ISO/ASTM NP 52903-3 Additive Manufacturing -- Standard Specification for Material Extrusion Based Additive Manufacturing of Plastic Materials -- Part 3: Part 3: Final parts		x	
	WK49229 Orientation and location dependence mechanical properties for metal additive manufacturing			x
	WK58229 Additive Manufacturing - Metallographic Evaluation of Metal Powder Bed Fusion Test Specimens and Parts *			x
Specific Process-Material	ASTM F3055 New specification for additive manufacturing nickel alloy (UNS N07718) with powder bed fusion	x		
	ASTM F3056 Specification for additive manufacturing nickel alloy (UNS N07718) with powder bed fusion	x		
	ASTM F2924-14 Standard specification for additive manufacturing titanium-6 aluminum-4-vanadium with powder bed fusion	x		
	ASTM F3001-14 Standard specification for additive manufacturing titanium-6 aluminum-4-vanadium eli (extra low interstitial) with powder bed fusion	x		
	ASTM F-3184-16 Standard specification for additive manufacturing stainless steel alloy (UNS S31603) with powder bed fusion	x		
	WK51329 Additive manufacturing Cobalt-28 Chromium-6 Molybdenum Alloy (UNS R30075) with Powder Bed Fusion1			x
	WK53423 Additive Manufacturing AlSi10Mg with Powder Bed Fusion			x
Finished parts/ applications	ISO/NP TR 52612 Design of functionally graded additive manufactured parts		x	
	WK56649 Standards practice/guide for intentionally seeding flaws in additevely manufactured (AM) parts			x
	WK58240 Additive Manufacturing - Grippers of Control Rod Drive Mechanism (CRDM) of Nuclear Power Plants			x

4 AM standardization gaps and barriers analysis

This section collects a list of main gaps and barriers based on the previous findings of SASAM and FoFAM projects, as well as the roadmap of additive manufacturing published by America Makes & ANSI Additive Manufacturing Standardization Collaborative (AMSC) last February 2017.[9]

The list is divided into the following topics corresponding to different segments of the AM-motion value chain:

- Modelling&Design,
- Materials
- Process (including equipment and post-processing)
- Product (including testing).

In addition, a general category and a sectorial analysis have been considered specifically for the medical and aerospace industry. This list of gaps will be used to define priority and the actions to tackle them to be discussed on expert sessions and included on AM roadmap (WP5) to be developed in 2018.

Table 4. *Summary table of standardization gaps*

General

Gap Name	Description
Increased industry engagement on standards development	To accelerate AM market take up, industry should be further engage in CEN, ASTM and ISO standars develpment. Possible barriers concerning time and money to follow this activity should be minimized.
Decision support: additive vs. substractive	A guidelines or a ISO/PAS publicly available specification would be useful for helping users understand the advantages/disadvantages of AM processes vs. traditional manufacturing processes while also providing decision criteria so informed design/manufacturing decision can be made.
Machine operator training and qualification	It is required to develop AM operator training and qualification standards or guidelines.

[9] AMSC Standardization Roadmap for Additive Manufacturing

Design

Gap Name	Description
Process-specific design guidelines	The design guideline for PBF is currently the sole process-specific design guideline available. There is development work in the pipeline to push to other process specific design guidelines, taking into account that ASTM and ISO identify 7 types of AM processes. Application-specific design guidelines for Medical Application is on-going as part of ISO/TC261/JG70.
Application-specific design guidelines	As industry fields mature in particular AM applications, best practices should be recorded. For example, design for assembly, for printed electronics, for medical, etc.
Design guide for surface finish post-processing	AM is challenged with meeting the surface finish requirements of many fatigue critical parts. Many third party surface enhancement processes (such as micro-machining, Isotropic Super Finishing, Drag Finishing, and laser micromachining) have been used to bring the finish to an acceptable level. A design guide is required to provide a means to design for these third party finishing enhancement techniques.
Design and manufacturing process feasibility	Since different AM processes have different design requirements, manufacturing requirements, and manufacturing capabilities (e.g., overhang angles, minimum member thickness, minimum hole diameter, etc.), it is often challenging to determine if a design is feasible for a given AM process. A standard for reporting machine inputs and capabilities is needed to enable design tools to determine manufacturing feasibility.
AM simulation	AM process simulation tools are becoming an important aspect of the AM design process by enabling the designer to understand and mitigate residual stress and process dependent deformation. A standard is needed to enable verification and validation of applicable process simulation tools.
Design documentation	In most cases, upon completion of an engineering design, there will be a requirement to completely document it. AM offers the capability to create new designs that were never conceived of before. Consequently, new standards are required to assist in the documentation of these designs. They should cover aspects such as content of a technical data package, new dimensioning and tolerancing requirements, definitive standard AM file format, terminology, documentation for in-process monitoring, documentation for new functional surface features, specification to procure parts from third parties, etc.
Design verification and validation	The verification and subsequent validation of a design are important steps to ensure it fulfills its goals and application. In this sense, standardization gaps have been identified regarding methods of configuration and version control as well as the measurement of AM features such as complex shapes or internal features.

Materials

Gap Name	Description
Precursor material properties	Precursor material requirements differ, even within one materials family, from one AM equipment manufacturer or application to another. While a large body of work pertaining to standard test methods is being carried out globally, more work is needed to address the variation in AM precursor materials. Standards and criteria are required for assesing the following precursor materials' parameters and link them with the AM process: flowability, spreadability, particle size/particle size distribution, particle morphology, presence of hollow particles, etc.
Powder specifications	There is a need to develop AM process-specific powder specifications to facilitate procurement of metal powders for use in AM machines.
Storage of materials	Guidance on storage of AM materials is needed.
Recycling powder	A standard is needed for the re-use of material that was already printed, as well as for the material that was not printed but is already within the system. Guideliness for sieving reused powder prior to mixing should be also created.

Process

Gap Name	Description
Machine calibration and preventive maintenance	Therea are no known industry standards addressing machine calibration and preventive maintenance.
Machine health monitoring	Therea are no known industry standards addressing AM machine health monitoring (observing the machinery to identify changes that may indicate a fault.
Parameter control	Standards are needed to identify requirements for demonstrating that a set of process parameters produces an acceptable part, and for ensuring that those process parameters remain consistent from build to build.
Adverse machine environmental conditions: effect on component quality	There is a need for developing standards and specifications to address external environmental factors that could negatively impact component quality.
Environmental Health and Safety (EHS)	There is a need for standards to address EHS in the AM process and teh protection of machine operators.
Cybersecurity	Best practices to protect digital files used in the AM process are required.
Hot Isostatic Pressing (HIP)	The existing HIP standards do not fully address AM material-related issues.
Process monitoring	No standards have been identified to address process monitoring. Standards should account for motion control components that guide measurement and remediation of error in positioning syetms where possible in AM machines.
Standard protocols for round robin testing	AM materials, equipment and process need to be qualified to repeatedly produce high-quality parts. The availability of several types of processes, machines and materials complicates this action. These protocols are needed to enable independent testing of processes and equipment and to establish trust on the technology.

Product

Gap Name	Context
Mechanical properties	It is neccesary to develop standards that identify the means to establish minimum mechanical properties for a specific material made by a given AM system using a given set of AM parameters for a given AM build design.
Microstructure	A standard for characterization and acceptance criteria of AM microstructures should be developed.
Dimensional metrology of internal features	Standards are needed for the dimensional measurement of internal features of AM objects.
Coupon testing	For a given application there is not a clear method or best practice document to help determine teh applicability and validity of coupon testing to a specific type of component or feature.
Nondestructive evaluation (NDE) methods	There is a need for standard test methods to accept/reject AM parts in the basis of nondestructive methods.
Terminology for the identification of AM flaws detectable by nondestructive evaluation	The development of standardized terminology to identify and describe flaws is required.

Sectorial gaps[10]

Gap Name	Description
Medical industry: Importing ultrasound data	The DICOM standard should be more widely promoted and potentially revised to enable data to be imported from any ultrasound equipment.
Medical Industry: Cleanliness and sterealization of medical AM parts	There are no standardized protocols or acceptance criteria to reproducibly measure and evaluate the cleanliness of a part with relevant, risk-based acceptance criteria. On the other hand, anatomical models may require sterilization if they are to come in contact with compromised tissue of patients. A guidance in this area is required.
Medical Industry: Personnel training for image data processing	Currently, there are only limited qualification or certification programs available for training personnel who are handling imaging data and preparing for AM printing.
Medical Industry: Verification of 3D model	There are currently no standards for the verification of the 3D model against the initial data before its approval for AM for the intended purpose (eg. surgical planning, implant, cutting guides, etc).
Medical Industry: Resorbable materials	It is neccesary to develop guidance on how to test the degradation of resorbable polymers to support material selection for AM.
Aerospace Industry: Application of standards for aerospace requirements	It is needed to show to the certification bodies that AM technical and industrial base could be in line with normal practices in the sector. Standards are required to develop a clear route to acceptance.

5 Acknowledgments

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[10] AM for the medical industry is now being developed and will be undertaken by ISO TC261/JG70.

6 Annex 1

Table 5. *ISO/TC 261 Structure. Working Groups*

Reference	Title
ISO/TC 261/AG 1	Coordination group
ISO/TC 261/AHG 3	Monitoring of data representation standards
ISO/TC 261/AHG 5	Content for ISO/TC 261 homepage
ISO/TC 261/CAG	Chairman's advisory group
ISO/TC 261/JAG	ISO/TC 261 - ASTM F42 Steering group on JG activities
ISO/TC 261/JG 51	Joint ISO/TC 261-ASTM F 42 Group: Terminology
ISO/TC 261/JG 52	Joint ISO/TC 261-ASTM F 42 Group: Standard test artifacts
ISO/TC 261/JG 55	Joint ISO/TC 261-ASTM F 42 Group: Standard Specification for Extrusion Based Additive Manufacturing of Plastic Materials
ISO/TC 261/JG 56	Joint ISO/TC 261-ASTM F 42 Group: Standard Practice for Metal Powder Bed Fusion to Meet Rigid Quality Requirements
ISO/TC 261/JG 57	Joint ISO/TC 261-ASTM F 42 Group: Specific design guidelines on powder bed fusion
ISO/TC 261/JG 58	Joint ISO/TC 261-ASTM F 42 Group: Qualification, quality assurance and post processing of powder bed fusion metallic parts
ISO/TC 261/JG 59	Joint ISO/TC 261-ASTM F 42 Group: NDT for AM parts
ISO/TC 261/JG 60	Joint ISO/TC 261-ASTM F 42 Group: Guide for intentionally seeding flaws in additively manufactured (AM) parts
ISO/TC 261/JG 61	Joint ISO/TC 261-ASTM F 42 Group: Guide for anisotropy effects in mechanical properties of AM part
ISO/TC 261/JG 62	Joint ISO/TC 261-ASTM F 42 Group: Guide for conducting round robin studies for additive manufacturing
ISO/TC 261/JG 63	Joint ISO/TC 261-ASTM F 42 Group: Test methods for characterization of powder flow properties for AM applications
ISO/TC 261/JG 64	Joint ISO/TC 261-ASTM F 42 Group: Solid modelling support
ISO/TC 261/JG 66	Joint ISO/TC 261-ASTM F 42 Group: Technical specification on metal powders
ISO/TC 261/JG 67	Technical report for the design of functionally graded additive manufactured parts
ISO/TC 261/JG 69	Joint ISO/TC 261-ASTM F 42 Group: EH&S for use of metallic materials
ISO/TC 261/JWG 5	Joint ISO/TC 261 - ISO/TC 44/SC 14 WG: Additive manufacturing in aerospace applications
ISO/TC 261/WG 1	Terminology
ISO/TC 261/WG 2	Processes, systems and materials
ISO/TC 261/WG 3	Test methods and quality specifications
ISO/TC 261/WG 4	Data and Design
ISO/TC 261/WG 6	Environment, health and safety

Table 6. *Liaison Committees from ISO/TC 261*

ISO/TC 261 can access the documents of the committees below:

Reference	Title	ISO/IEC
IEC/TC 76	Optical radiation safety and laser equipment	IEC
ISO/IEC JTC 1	Information technology	ISO/IEC
ISO/TC 44	Welding and allied processes	ISO
ISO/TC 44/SC 5	Testing and inspection of welds	ISO
ISO/TC 44/SC 14	Welding and brazing in aerospace	ISO
ISO/TC 61	Plastics	ISO
ISO/TC 61/SC 9	Thermoplastic materials	ISO
ISO/TC 119	Powder metallurgy	ISO
ISO/TC 135	Non-destructive testing	ISO
ISO/TC 150	Implants for surgery	ISO
ISO/TC 156	Corrosion of metals and alloys	ISO
ISO/TC 184	Automation systems and integration	ISO
ISO/TC 213	Dimensional and geometrical product specifications and verification	ISO
ISO/TC 292	Security and resilience	ISO

Table 7. *Liaison Committees to ISO/TC 261*

The committees below can access the documents of ISO/TC 261:

Reference	Title	ISO/IEC
IEC/TC 76	Optical radiation safety and laser equipment	IEC
ISO/IEC JTC 1	Information technology	ISO/IEC
ISO/TC 39	Machine tools	ISO
ISO/TC 44	Welding and allied processes	ISO
ISO/TC 44/SC 14	Welding and brazing in aerospace	ISO
ISO/TC 119	Powder metallurgy	ISO
ISO/TC 150	Implants for surgery	ISO
ISO/TC 150/SC 1	Materials	ISO
ISO/TC 184/SC 1	Physical device control	ISO
ISO/TC 184/SC 4	Industrial data	ISO
ISO/TC 292	Security and resilience	ISO