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Analysis of General and Specific Standardization Developments in Additive Manufacturing From a Materials and Technological Approach

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AQ:3 **ABSTRACT** Additive manufacturing processes and products are very present in the current productive landscape, and in fact these technologies have been one of the most intensively studied and improved during the last years; however, there is still no defined and homogeneous regulatory context for this field. In this work, a thorough review of the main general and specific regulatory developments in design, materials and processes standards for additive manufacturing has been carried out, with special attention to the standards for mechanical characterization of polymer-based products. In many cases standards developed for other productive contexts are identified as recommended references, and some contradictory trends can be identified when different documents and previous experiences are consulted. Thus, as it is logical considering that all these technologies are involved in an intensive and continuous evolution process, there is a certain lack of clarity regarding the standards to be considered. This work aims to contribute to clarify the current standardization context in additive manufacturing and provide some guidelines for the identification of appropriate standards. The paper also emphasizes that the key for next regulatory developments in mechanical testing is to develop standards that consider particular AM processes along with materials. Moreover, a great gap between available standard about additive technologies based on metallic materials and polymer materials during the last years has been detected. Finally, the provided overview is considered of interest as support for research and practice in additive manufacturing, and both in intensive productive scenarios and for particular users and makers.

INDEX TERMS Standardization, additive manufacturing, ASTM, ISO.

I. INTRODUCTION

Nowadays additive manufacturing is a consolidated reality. A significant number of very different technological alternatives are included under this category [1]; the materials used [2]–[4], the applications [5], [6], benefits and challenges are constantly increasing [7]–[9] and the corresponding processes are being deeply studied, not only from technological approaches, but also in relation to their role in future productive scenarios [10] and considering other aspects such as economic [11], [12], sustainability [13] or even security issues [14]. Additive manufacturing technologies are widely established both in our industries and in the collective knowledge of society. This special social acceptation of additive manufacturing, especially in regard to 3D printing with polymer materials, has also contributed to the significant rise of these technologies during last years, and today the inclusion of additive manufacturing issues in educational scenarios have been also strongly promoted [15], [16].

The validation of the products obtained through certain production processes represents their final adequacy and integration in the industrial field, in which the quality assurance

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of the products is both a need and an objective. In that sense, it is worth asking whether products obtained through additive manufacturing can offer these guarantees today. The results obtained through these additive technologies are of great interest because of their new possibilities compared to traditional productive technologies and also the properties of their products demonstrate functional capacity in service; but it is necessary to demonstrate the real capacity to produce robust products of sufficient quality [7], [17] and standardization is the way to go [18].

However, the incorporation of these technologies into the productive field is still incipient and these technologies themselves are in constant evolution. In that context, and although great efforts are being made, the current standards to guide the standardization of these processes and their products is still scarce and insufficient. A clear example of this situation is the lack of standards for the mechanical characterization of the parts obtained with these technologies [19], [20]. For different materials, main general standards on additive manufacturing identify previous standards on test methods; but there is not always consensus on what those references should be and furthermore their applicability is relative in practice [21].

The great increase in access to additive technologies, especially the ones based on polymers and concretely FDM, means that a large volume of products outside the industrial framework are being used. Currently, polymer 3D printers are no longer strange items even in a home. And the parts produced in these domestic scenarios will be used exactly the same than those bought in a shop. Therefore, the ability of standards to validate products obtained with additive technologies must also be able to reach these particular contexts. Special situations, such as those experienced during the COVID-19 crisis [22], [23], and the urgent needs of certain devices have defined scenarios in which the productive capacity of the traditional industries is not flexible enough and these individual or domestic productive centers can have a key role. In that context, the agility and adaptability of additive manufacturing technologies and also the collective productive capacity of 3D printers has been proved [24]–[30], and the importance of guaranteeing the appropriate quality of the obtained products has been revealed.

Thus, in this work, a review of the currently available standards applicable to additive manufacturing technologies is carried out, with special attention to design and materials, identifying the appropriate test methods for the characterization of the pieces obtained through these processes. A characterization that, although it takes into account aspects of diverse nature, in practice focuses the development of regulations in the mechanical behavior of the pieces and in the appropriate tests to determine the associated values. To achieve this goal, an approach to the problem is made in 3 successive steps.

☐ Analysis of the general standards on additive manufacturing.

☐ Identification of the specific testing standards referred to in the general standards on additive manufacturing for tests with this type of products, paying special attention to tensile and compression tests.

☐ Review of the existing scientific literature in this field to verify the coincidence or not of the standards used as a reference in those works with the ones identified in the previous step.

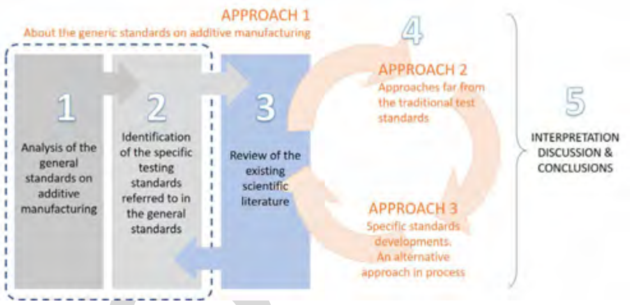


FIGURE 1. **Work methodology.**

Through these three successive steps the standards most commonly used for compression and tensile tests with plastic parts obtained by additive manufacturing are identified.

Additionally, other considerations and approaches are commented. Firstly, the anisotropic nature of additive manufacturing parts is analyzed, since their fabrication layer by layer carries a great influence of the manufacturing orientation. Moreover, the deposition of the material in each layer and the existing gaps between the beads are aspects which make the standards previously identified difficult to apply [19], [21], [31].

Secondly, cellular and lattice structures, as design strategies highly powered by additive manufacturing, are identified as scenarios of great interest on the field of additive manufacturing, but which are far from the standards identified as references for the mechanical characterization of these products in the standards of additive manufacturing [21], [32]–[34].

Finally, much more specific standardization initiatives are identified as the probably most viable approach for the development of standards on additive manufacturing issues, as opposed to the general standards on additive manufacturing identified, which applicability proves to be too relative and often limited. All these specific standards are analyzed and compared from different approaches. Their importance for different materials and processes is commented, and an overview of current standardization for additive manufacturing products and processes is proposed.

II. ABOUT THE GENERIC STANDARDS ON ADDITIVE MANUFACTURING

A. INITIAL APPROACH TO THE REGULATIONS ON ADDITIVE MANUFACTURING

When talking about the reference standards for the performance of mechanical tests, the two obligatory references are the International Organization for Standardization (ISO) and the American Society for Testing and Materials (ASTM). These organizations elaborate the standards commonly used in this type of tests for the characterization of materials and parts. Within the families of standards that both organizations offer, regulations regarding additive manufacturing can be found.

In this sense, it is possible to make a first differentiation regarding the approach of these documents since in their contents, aspects of a very different nature are addressed. Thus, in this work an initial differentiation is made, identifying those standards, or parts, related to the contextual and theoretical framework of additive manufacturing, that includes the terminology, definitions, technologies and processes of this type of manufacturing; and those ones related to the standardization of the tests to be performed for the characterization of the pieces obtained as a result of these processes. The second part of the ISO 17296:2015 entitled "Overview of process categories and raw materials" is an example of the first of these situations, while the third part of the same standard, entitled "Main characteristics and corresponding test methods", exemplifies the second situation [35], [36].

Sometimes, in addition to the main standards developed by these international organizations, it is possible to identify standards developed by national organizations. The Spanish Association for Standardization (UNE), publishes the Spanish version of the standards developed by the ISO and it also develops its own standards. That is the case of the UNE 116005:2012, focused on tensile tests of specimens obtained by additive manufacturing with polymer materials [37].

Thus, in Table 1 the standards for additive manufacturing identified are grouped into two families of standards; the different parts of the ISO 17296 [35], [36], [38] and the ISO/ASTM standards on additive manufacturing [39]–[43]. It can also be seen that in the case of the ISO 17296 the first part of this standard is pending publication, and as other works have pointed out, it is expected that this new document clarifies some aspects regarding terminology [20].

From that first distinction, in the columns on the right the focus of the content of each of the standards identified, or of each of the parties in the case of ISO 17296, has been indicated. On the one hand, the contents more oriented to the description of this type of technologies and processes, which contribute to defining what could be called the theoretical framework of reference for additive manufacturing, are distinguished. On the other hand, the contents aimed at conducting tests on the pieces obtained are indicated.

Table 1 shows how through the standards grouped within these two blocks both approaches are covered, the one related to the theoretical framework and the one related to the development of tests. On the other hand, previously mentioned UNE 116005:2012 is fully oriented to the performance of mechanical tests, specifically tensile tests, and only with polymeric materials.

TABLE 1. **Classification of the standards identified on additive manufacturing according to their approach and the type of materials considered.**

	Approach		Material		
	Theoretical framework	Tests	Metal	Plastic	Ceramic
ISO 17296-2:2015 Additive Manufacturing General principles. Part 2: Overview of process categories and raw materials.	■				
ISO 17296-3:2014 Additive Manufacturing - General principles. Part 3: Main characteristics and corresponding test methods.		■	■	■	■
ISO 17296-4:2014 Additive Manufacturing General principles. Part 4: Overview of data exchange.	■				
ISO/ASTM 52900:2015 Additive Manufacturing General principles. Terminology.	■				
ISO/ASTM 52901:2017 Additive manufacturing. General principles. Requirements for purchased AM parts	■				
ISO/ASTM 52910:2018 Additive manufacturing – Design - Requirements, guidelines and recommendations	■		■	■	
ISO/ASTM 52915:2020 Specification for additive manufacturing file format (AMF) Version 1.2	■				
ISO/ASTM 52921:2013 Standard terminology for additive manufacturing. Coordinate systems and test methods.		■			

With regard to the work materials considered in each of the standards identified in Table 1, some observations may also be made. As the three columns to the right of the table show, ISO 17296 considers the three categories of materials; polymers, metals and ceramic materials. On the other hand, ISO/ASTM standards are oriented to polymeric and metallic materials, but they do not consider ceramic materials. Unlike these multimaterial approaches, the mentioned UNE 116005:2012 is exclusively oriented to polymeric parts.

Of the standards identified, this work pays special attention to the ones oriented to the development of mechanical tests. The mechanical testing of parts obtained by additive manufacturing is an unclear aspect today and it is a hot topic of debate among the scientific community.

In that sense, as indicated in Table 1, two documents should be highlighted. The ISO 17296-3:2014 [36], which corresponds to the third part of this regulation for additive manufacturing and which identifies the test methods to be used for different materials. And the ISO/ASTM 52921:2013 [43] developed by the ASTM. However, different authors have indicated in their work that specific regulation about testing for mechanical characterization of parts in additive manufacturing [19], [31] is currently not sufficient enough. Thus, the standards presented in Table 1 refer to other standards of conventional testing methods that may be of application, but which in no case have been specifically developed for these technologies.

As noted above, in general, these standards on additive manufacturing identify others that may be applicable to additive manufacturing parts, but which really correspond to regulatory developments which are specific to other productive and technological contexts. The clearest example of this circumstance is found in the case of the ISO 17296-3:2014. That standard includes a table identified as Table 4 in which a wide number of consultation standards are identified according to the material and the type of test. Thus, as shown in Table 2, a total of 139 standards are identified by the ISO 17296-3:2014 as references for testing parts obtained by additive manufacturing with different materials and in order to determine their quality in relation to different characteristics or requirements. However, it should be noted that this number is reduced to 92 when matches are considered. For example, for surface and geometric requirements the same standards are indicated for metallic materials, as plastics and ceramics. On the contrary, in the case of the mechanical requirements different standards are identified for each type of material.

TABLE 2. **Classification of the standards identified in the ISO 17296-3:2014 for carrying out tests associated with different quality requirements in parts obtained by additive manufacturing.**

Quality requirements	metal	plastic	ceramic	Total of references	Total of different references
raw material	9	9	11	29	21
surface	7	7	7	21	7
geometric	7	7	7	21	7
mechanical	11	23	15	49	48
manufacturing material	7	6	6	19	9
total	41	52	46	139	92

As can be seen when consulting the standards identified by ISO 17296-3:2014, all these mechanical test standards are characteristic of other productive and technological contexts, which are different from additive manufacturing. In that sense, ISO 17296-3:2014 itself indicates that efforts are being made to define and describe the specific characteristics of the products obtained by additive manufacturing, and that the standards indicated are temporary recommendations until specific standards are available [36]. This way, the applicability of all these recommended standards is limited in the context of additive manufacturing, and it depends largely on the way in which the infill of the piece is conceived [21].

The standard ISO/ASTM 52921:2013 is focused mainly on standardizing the terminology for the test results reports and defining the correct location and orientation of the pieces in the construction volume. It does not include such a comprehensive review of the possible consultation regulations for testing. But in its second section, called Norms for consultation, several standards specific to other productive and technological contexts and which are considered useful for additive processes are identified. Table 3 shows the regulations referred for consultation in the ISO/ASTM 52921:2013.

TABLE 3. **Standards referred to by ISO/ASTM 52921:2013.**

	Classification by material		Other aspects
	Plastics	Metals	
ASTM	**D638** Standard Test Methods for Tension Properties of Plastics	**E8/E8M** Test Methods for Tension Testing of Metallic Materials	**F2792** Terminology for Additive Manufacturing. Technologies
ISO	**ISO 527** (all parts) Plastics. Determination of tensile properties	**ISO 6892-1** Metallic materials. Tensile testing. Part 1: Method of test at room temperature	**ISO 841** Industrial Automation Systems and Integration. Numerical Control of machines. Coordinate System and Motion Nomenclature

The smaller amount of references in comparison to the information shown in Table 2 for the case of ISO 17296-3 can be clearly seen. In this regard, it is especially noteworthy that in this case ceramic materials are not considered, as already indicated in Table 1. In addition, for the materials considered, this is plastics and metals, the type of test considered when identifying consultation standards is only tensile tests. Different from ISO 17296, ISO/ASTM 52921:2013 does not identify consultation standards for any other mechanical test, not even for compression tests.

As a summary, Table 4 shows the different approaches to the problem that are made from the identified standards for additive manufacturing. On the one hand, it is clear that the only standard that really offers a complete selection of standards to be taken into account for tests on parts obtained by additive manufacturing is the ISO 17296-3: 2017, both in relation to work materials and types of tests. And, on the other hand, it can be seen that the tensile tests on plastic materials have focused the most attention in these documents.

Thus, the current state of the regulations in the field of mechanical characterization of additively manufactured parts

TABLE 4. Mechanical tests for which consultation standards are identified in the standards ISO 17296-3:2017 and ISO/ASTM 52921:2013.

		Metals	Polymers	Ceramics
Geometric requirements	Dimensional tolerances	■	■	■
	Geometric tolerances	■	■	■
Mechanical requirements	Hardness	■	■	■
	Tensile	■ □	■ □	■
	Impact	■	■	■
	Compression	■	■	■
	Flexure	■	■	■
	Fatigue	■	■	■
	Creep	■	■	■
	Aging	■	■	■
	Friction	■	■	■
	Shear	■	■	■
	Crack propagation	■	■	■

■ ISO 17296-3:2014 □ ISO/ASTM 52921:2013

is still precarious and provisional, especially as regards the testing of parts. On the one hand, there are identified and referred standards developed for productive contexts very different from that of additive manufacturing [21]. And, on the other hand, in regard to these standards that could be considered as "framework", it is the tensile tests in polymeric materials that have the most normative basis at present, while for other materials and for other types of tests the normative references are significantly lower. Fig. 2 proposes a graphic and schematic representation of this situation as a summary of the analysis carried out in this section.

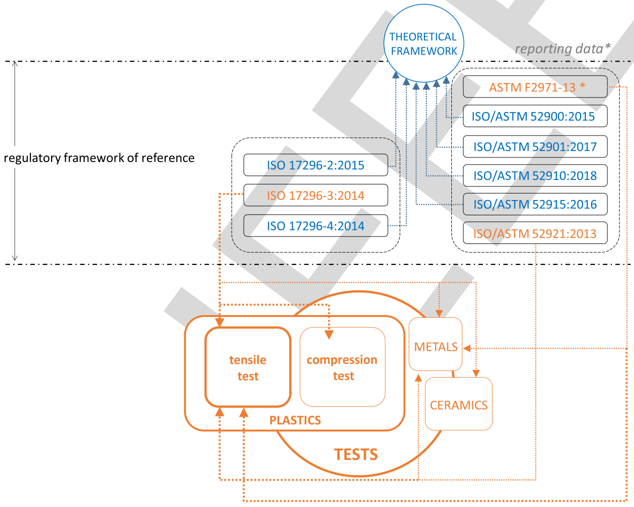


FIGURE 2. Contributions of current regulations on mechanical characterization of parts produced by additive manufacturing.

B. SPECIFIC STANDARDS FOR TESTING POLYMERIC PARTS OBTAINED BY ADDITIVE MANUFACTURING

After the initial approximation made to the current development of the standards in the field of additive manufacturing in general, this study is focused on the standards related to the mechanical testing of parts, and concretely parts made of plastic materials. As exposed before, it is precisely in the field of polymeric materials that there is a greater documentary reference for the mechanical testing of parts obtained by additive manufacturing, which represents a starting advantage. Moreover, plastics were the first materials used in additive manufacturing, and the only ones for a long time, so more expertise and tradition are expected.

The most common or basic mechanical tests in order to obtain resistance values for the materials considered are the tensile and the compression tests. Bending stresses are also of great interest because of their usual presence in service conditions. However, in these tests, breakage occurs in the tensile zone and provide values normally higher than those of the single tensile test for the same material; so usually the tensile test can be considered the main reference since it represents the most unfavorable situation. Thus, focusing the analysis on tensile and compression tests, Table 5 reflects how the ISO 17296-3:2014 identifies consultation standards for both types of tests, while ISO/ASTM 52921:2013 only refers to tensile tests, not compression tests.

TABLE 5. Standards for tensile and compression tests for plastic materials identified in the international standards on additive manufacturing.

	TENSILE	COMPRESSION
ISO 17296-3:2014	ISO 527	ISO 604
ISO/ASTM 52921:2013	ISO 527 ASTM D638	-

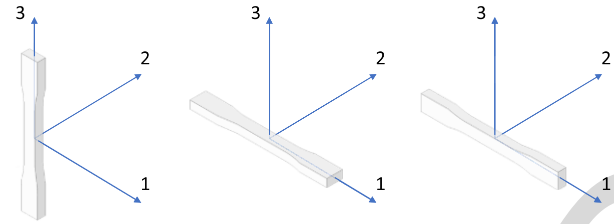
From the ISO 17296-3:2014, ISO 527 [44]–[48] and ISO 604 [49] are the standards identified for tensile and compression tests, respectively. ISO 527 is also the standard that identifies the standard UNE 116005:2012 as reference for tensile test. In the case of ISO/ASTM 52921:2013, two standards for tensile testing are identified, ISO 527 and ASTM D638 and no standard is identified for the compression test.

1) REGULATIONS RELATING TO TENSILE TESTS

As can be seen in Table 5, the standard ISO 527, which is oriented to the determination of tensile properties in plastic materials, is considered in the three standards on additive manufacturing. In turn, this standard has five different parts (Table 6). The first one addresses the general principles [44], and the following four establish the conditions to determine the tensile properties in molding and extrusion plastics, films and sheets, and isotropic and orthotropic fiber-reinforced plastic composites, respectively [45]–[48]. Thus, the second part, ISO 527-2:2012, is oriented to the testing of plastics for molding and extrusion, and that case is understood as the one closer to FDM manufacturing process, as already identified in other works [31]. However, the layer by layer morphology

TABLE 6. **Parts of the standard ISO 527 for tensile tests of plastics.**

International Standard	Date
ISO 527-1:2019 Plastics — Determination of tensile properties — Part 1: General principles	2019-07
ISO 527-2:2012 Plastics — Determination of tensile properties — Part 2: Test conditions for molding and extrusion plastics	2012-02
ISO 527-3:2018 Plastics — Determination of tensile properties — Part 3: Test conditions for films and sheets	2018-11
ISO 527-4:1997 Plastics — Determination of tensile properties — Part 4: Test conditions for isotropic and orthotropic fiber-reinforced plastic composites	1997-04
ISO 527-5:2009 Plastics — Determination of tensile properties — Part 5: Test conditions for unidirectional fiber-reinforced plastic composites	2009-07



vertical position (type 1A)

horizontal position (type 1A)

edgewise position (type 1AV)

FIGURE 3. **Representation of possible orientations in parts obtained by additive manufacturing based on UNE 116005:2012.**

of the pieces obtained does not really correspond to the ones obtained through those processes, so this approach must be understood as temporary, and be used while developing specific standards, as indeed the standard UNE-EN ISO 17296-3:2014 already indicates [36].

Previously mentioned UNE 116005:2012 also refers to ISO 527 for tensile testing of parts obtained by additive manufacturing with plastics. However, with regard to the description and identification of the specimens, UNE 116005:2012 includes some aspects that are considered noteworthy against the information provided in part 1 and part 2 of ISO 527. Thus, three test tube orientations are explicitly distinguished. First, from a general approach to any piece obtained by additive manufacturing, by identifying three axes associated with three possible orientations or positions of the specimen. Subsequently, representations of the three orientations for the tensile specimens are included [37].

The standard referred for tensile tests in both UNE 116005:2012 and ISO 17296-3:2014 is ISO 527. But, regarding the geometric specifications of the specimens, although the standard UNE 116005:2012 includes tables of specifications in which it is possible to identify some small differences with the information included in ISO 527-2. Comparing the graphical representations of the specimens that both standards include, it is possible to appreciate that in both cases the same geometric parameters for the definition of the specimens are considered.

TABLE 7. **Comparison of geometric specifications for type 1A specimens according to ISO 527-2:2012 and UNE 116005:2012.**

	ISO 527-2:2012		UNE 116005:2012	
	Geometric parameters	Type 1A (mm)	Type 1A (mm)	Geometric parameters
l_1	Length of the narrow part of parallel faces	80 ± 2	80 ± 2	Narrow parallel zone length
l_2	Distance between wide parts of parallel faces	109,3 ± 3,2	104 a 113	Distance between wide parallel zones
l_3	Total length	170	≥ 150	Total length
r	Radius	24 ± 1	20 a 25	Radius
b_1	Narrow part width	10,0 ± 0,2	10,0 ± 0,2	Narrow part width
b_2	Width at ends	20,0 ± 0,2	20,0 ± 0,2	Width at ends
h	Recommended thickness	4,0 ± 0,2	4,0 ± 0,2	Recommended thickness
L_0	Reference length (recommended)	75,0 ± 0,5		
	Reference length (acceptable if required for quality control or when specified)	50,0 ± 0,5	50,0 ± 0,5	Distance between marks
L	Initial distance between the jaws	115 ± 1	115 ± 1	Initial distance between the jaws

Thus, Table 7 compares the values established in both standards for the geometric parameters identified. Only the values included in each standard for type 1A specimens are collected. Type 1AV of standard UNE 116005:2012 is discarded due to its vertical orientation, which has already identified as nor appropriate for this test in other works [31]. And neither the type 1B of standard ISO 527-2:2012 is considered, since it considers mechanized specimens.

Using a solid background, the fields for which the values associated with the parameters considered coincide in both standards are identified. The rest of the situations do not represent contradictions, although, as a general conclusion, it can be said that in those cases the values provided by the ISO 527 standard are more restrictive or they are limited to smaller ranges of values.

In any case, they are small deviations. But, perhaps the approach to the problem of UNE 116005:2012 and the geometric specifications that establish have an added interest in the context of additive manufacturing, at least as a particular experience in this field, UNE 1160005:2012 is developed since the beginning for additive manufacturing processes, and the characterization of the specimens is made from that perspective and considering key aspects for these processes, such as the possible orientations of the specimen according to the orientation of the layers. On the other hand, the type 1A specimen described by ISO 527-2:2012 is presented as the typology to be used when the specimens are molded by injection or compression. UNE 116005:2012 does not really provide many new aspects or considerations compared to ISO 17296-3. In both cases ISO 527 is the main reference. But this standard has interest since it concentrates in a single document, aspects which appear dispersed in different standards when main standards on additive manufacturing are considered. And it also provides a presentation focused on additive manufacturing scenarios since the beginning. Thus, consulting this kind of document can provide complementary information with practical application.

As indicated in Table 5, the standard ISO/ASTM 52921:2013 identifies, in addition to the already mentioned ISO 527, the ASTM D638-14 standard as a reference for tensile tests [50]. In the sixth point of this standard five types of test specimens are identified, being Type I, which corresponds to rigid or semi-rigid plastics with thicknesses of 7 mm or less, the one that fits the context of this work. Type II will only be considered if the test specimens of Type I do not fracture in the part corresponding to the narrow section. The rest of typologies respond to other contexts that are not of interest for this work; thus, Type III will be used when the thicknesses must be greater than 7 mm without exceeding 14 mm, while Type V will be used when the thicknesses must be 4 mm or less. On the other hand, Type IV will be applied when it is required to make direct comparisons between materials with different stiffness, that is to say semi-rigid and not rigid.

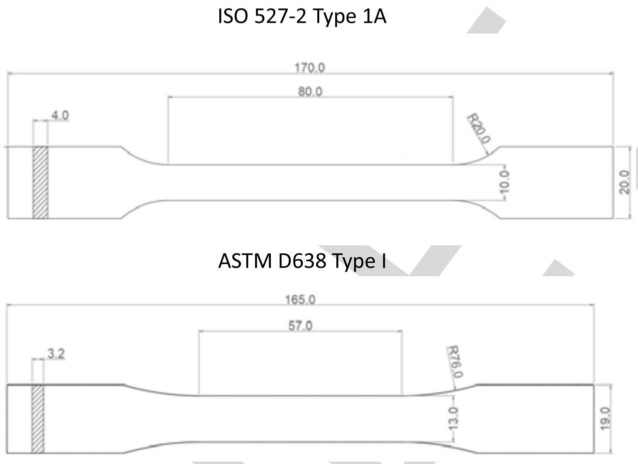


FIGURE 4. **Fundamental dimensions of the specimens considered for tensile tests according to ISO 527-2and ASTM D638-14.**

Fig. 4 shows the specimens considered by ISO 527-2 and ASTM D638-14. It can be seen that there are some differences between both geometries. Perhaps the most striking aspect is the greater slenderness of the fracture zone in the case of the test specimen defined by the UNE 116005:2012 and ISO 527-2 standards compared to the test specimen defined by ASTM D638-14, with widths of 10 and 13 mm, respectively. Nevertheless, the thickness of 4 mm versus the 3.2 mm established by the ASTM D638 standard makes the resistant sections quite similar, with 40.0 mm2 and 41.6 mm2 respectively.

2) REGULATIONS RELATING TO COMPRESSION TESTS

Similarly, a search for regulations for compression tests was carried out. The first step is to consult the call to test standards that are made from the regulations on additive manufacturing. In that sense, Table 5 showed that only the ISO 17296-3:2014 standard on additive manufacturing identifies a reference standard for the compression test with plastic materials, the ISO 604:2002 [49]. The other standards on additive manufacturing, that means UNE 116005:2012 and ISO/ASTM 52921:2013, do not identify consultation standards for compression test.

In this way, the ISO 604:2002 standard remains the only regulation for these tests that is referred to in the current specific regulations for additive manufacturing. However, taking into account the usual practice in the scientific literature on these topics, the use of ASTM D695-15 [51] is obvious when carrying out this type of tests on these pieces. This situation is addressed in the following section, which completes the exposed revision of the existing regulations through experiences in this field.

C. APPROACH TO USUAL PRACTICES WHEN TESTING PARTS OBTAINED BY ADDITIVE MANUFACTURING

The analysis exposed so far on the general standards on additive manufacturing and the specific standards that from them are referenced for the performance of different kinds of tests has served to identify certain deficiencies. For example, not for all materials and types of test the standards identified on additive manufacturing propose sufficient consultation standards. In that context it is necessary to fill these deficiencies through the review of scientific production in this field, identifying the usual practices on mechanical testing of parts obtained by additive manufacturing. And in fact, this information can be considered itself as a reference sufficiently contrasted and as a starting point to raise similar experiences.

Two trends or work lines can be distinguished in this regard:

☐ In some works, the authors consider standards for mechanical testing for parts obtained by other manufacturing processes, executed with polymers as well as with ceramic or metallic materials, and then they apply these standards to similar testing of parts obtained by additive manufacturing.

☐ Other works discard these standards due to the nature of the pieces obtained by additive processes, whose structure does not conform to that continuous and isotropic behavior, quite the opposite, due to characteristic aspects of additive processes, such as layered construction and its orientation, or the filling patterns applicable to parts in some processes [1], [19], [21].

Tables 1, 2 and 4 allow to appreciate the complete compilation of ISO standards that ISO 17296-3:2014 includes. To get a similar list for the standards developed by ASTM International it is necessary a revision of previous experiences about different types of tests carried out with 3D printed parts, such as compression, flexion or others, and also for different materials, such as plastics, metals or composites. An in-depth review was made, and different works were identified. The works of Brischetto *et al.* [52] and Banjanin *et al.* [53] are examples of this type of studies in this case both oriented to compression tests. In the work of Brischetto *et al.* a thorough study of the compression properties of ABS specimens obtained by FDM is carried out. The reference taken as a reference in that study is ASTM 695-15, but it is indicated that technically this standard is equivalent to ISO 604:2002, which is the one identified by 17296-3:2014. In the same way, ASTM 695-15 is also identified as the reference for this essay in the work of Banjanin *et al.*

In this sense, and in relation to plastic materials, of special interest in the framework of this work, the authors consider that the work developed by Forster in 2015 [19] is still the reference of most interest and usefulness. The main quality of this work compared to others is that it is not a study focused on a specific test, but a compilation of the regulations of interest for a wide variety of mechanical tests applicable to these materials. The summary tables included in section 8 of said document are of special interest. In them, the standards of potential interest are identified for each test, indicating and justifying in each case the applicability or not in the case of parts obtained by additive manufacturing.

Thus, the work developed by Forster can be highlighted firstly by its usefulness in order to identify standards that can serve as a reference when carrying out tests of very different types on parts obtained by additive manufacturing. This aspect turns this work into a cross reference to a certain variety of mechanical tests. And from that point of view, it also establishes a certain similarity with ISO 17296-3:2014. But it should be noted that not all the types of tests identified in ISO 17296-3:2014 are considered in Forster's work, and similarly, Forster's work includes tests not referred in ISO 17296-3:2014, such as the torsion test.

Secondly, it should be noted that Forster's work only refers to polymeric materials, and it does not include a similar revision for metallic and ceramic materials, what ISO 17296-3:2014 includes. On the other hand, Forster's work includes standards for reinforced plastic materials. The authors of the present work consider appropriate to distinguish both situations as different realities, that is, polymeric materials and polymer matrix composites.

A third aspect to comment on the identification of standards carried out by Forster is the acceptance or not that after the initial identification is carried out. Three scenarios regarding the applicability in the field of additive manufacturing of the standards are identified: yes, yes with guidance and no [19]. None of the standards that Forster identifies in its work is validated with a yes, what would mean the total acceptance or an acceptance free of considerations and/or modifications. Thus, the standards identified are accepted with objections or directly rejected for use in additive contexts, what reinforces the idea that there is a need of specific and really appropriate standards to perform these mechanical tests on parts obtained through additive technologies.

To incorporate the commented aspects of Forster's work into the proposed analysis, the comparison shown in Table 4 is completed in Table 8 including an icon or box to identify the contributions of Forster's work, and a column related to composite materials. Obviously, the standards initially identified but then rejected in Forster's work has not been included in Table 8. Thus, in cases such as compression tests, Table 8 does not reflect regulations for composite materials based on Forster's work, because although standards for this type of test and that type of material are identified, specifically ISO 14126:1999 [54] and ASTM D3410/D3410M-03 [55], both are discarded for application in the field of additive manufacturing.

TABLE 8. **Mechanical tests for which consultation standards are identified in the standards ISO 17296-3:2017, ISO/ASTM 52921:2013 and UNE 116005:2012, as well as in the work of Forster [15].**

		Metals	Polymers	Ceramics	Composites
Geometric requirements	Dimensional tolerances	■	■	■	
	Geometric tolerances	■	■	■	
Mechanical requirements	Hardness	■	■	■	
	Tensile	■ □	■ □ ○	■	■ ○
	Impact	■	■ ○	■	
	Compression	■	■ ○	■	
	Flexure	■	■ ○	■	○
	Fatigue	■	■	■	■ ○
	Creep	■	■ ○	■	
	Aging	■	■	■	
	Friction	■	■	■	
	Shear	■	■	■	■ ○
	Crack propagation	■	■	■	
	Torsion		○		
	Fracture toughness				○
	Bearing strength and open hole compresion		○		○

■ ISO 17296-3:2014 □ ISO/ASTM 52921:2013 ○ Forster, 2015

The analysis of Table 8 shows interesting situations. For example, for the shear test it can be seen how Forster's work identifies standards applicable to the field of additive manufacturing, but related to composite materials, not to non-reinforced plastic materials. And, on the other hand, the table shows that ISO 17296-3:2014 provides a reference standard for this type of test and that type of material, the standard ISO 14129:1997 [56].

It can also be seen how ISO 17296-3 identifies consultation standards for composite materials for tensile, fatigue and shear tests. This is relevant since at first it only considers metallic, polymeric and ceramic materials. As in the case of Forster's work which refers to polymeric materials, polymer matrix composite materials are considered in the aforementioned documents as a type of plastic materials, while in the

TABLE 9. **Comparative summary of the consultation standards identified by ISO 17296-3:2014, ISO/ASTM 52921:2013 and Forster's work.**

	METALS			POLYMERS			REINFORCED PLASTIC COMPOSITES			CERAMICS		
	ISO 17296-3:2017	ISO/ASTM 52921:2017	Forster, 2015	ISO 17296-3:2017	ISO/ASTM 52921:2017	Forster, 2015	ISO 17296-3:2017	ISO/ASTM 52921:2017	Forster, 2015	ISO 17296-3:2017	ISO/ASTM 52921:2017	Forster, 2015
Hardness	ISO 6507			ISO 2039 ISO 868						ISO 14705		
Tensile	ISO 6892-1	ISO 6892-1 E8/E8M		ISO 527-1 ↔ ISO 527-2 ↔ ISO 527-3 ↔	ISO 527-1 ISO 527-2 ↔ ISO 527-3 D638 ↔	 ISO 527-2 D638	ISO 527-4 ↔ ISO 527-5 ↔	ISO 527-4 ↔ ISO 527-5 ↔	ISO 527-4 ~~ISO 527-5~~ ASTM D3039	ISO 15490		
Impact	ISO 148-1 ISO 148-2 (charpy)			ISO 179-1 ↔ ISO 179-2 (char.) ↔ ISO 180 (izod) ↔		ISO 179-1 ISO 179-2 (charpy) ISO 180 (izod) ASTM D256-10 (izod) ASTM D6110-10 (charpy)				ISO 11491		
Compression	ISO 4506			ISO 604 ↔		ISO 604 ASTM D695-10			~~ISO 14126:1999~~ ~~ASTM D3410/D3410M-03 (2008)~~	ISO 17162		
Flexure	ISO 3327			ISO 178 ↔		ISO 178:2010 ASTM D6272-10 ↔ ASTM D790-10 ↔			 ASTM D6272-10 ASTM D790-10 ~~ASTM D7264/D7264M-15~~	ISO 14704 ISO 14610		
Fatigue	ISO 1099 ISO 1143			ISO 15850 ↔		ISO 15850 ASTM D7774-12 ASTM 7791-12	ISO 13003 ↔		ISO 13003 ~~ASTM D6115-97(2011)~~	ISO 22214 ISO 28704		
Crack propagation	ISO 22889			ISO 15850						ISO 15732 ISO 18756 ISO 24370 ISO 23146		
Creep	ISO 204			ISO 899-1 ↔ ISO 899-2 ↔		ISO 899-1 ISO 899-2 ASTM D2990-09				ISO 22215		
Aging	Not relevant			ISO 4892-1 ISO 4892-2 ISO 4892-3 ISO 4892-4						Not relevant		
Friction	No identified standard			ISO 6601						ISO 20808		
Shear	ISO 148-1						ISO 14129 ↔		~~ISO 14129~~ ~~ASTM D3518/D3518M-13~~ ~~ISO 14130:1997~~ ~~ASTM D2344/2344M-13~~ ISO 15310:1999 ~~ASTM D4255/D4255M-01(2007)~~ ~~ASTM D7078/D7078M-12~~ ~~ASTM D3846-08~~	ISO 14129* _*for reinforced plastic composites_		
Torsion				ISO 458-1:1985								
Fracture toughness						ISO 13586:2000 ~~ISO 29221:2014~~ ASTM D6068-10			~~ISO 15024:2001~~ ~~ASTM D5528-13~~ ISO 13586:2000/Amd 1:2003			
Open-hole compression strength						ASTM D953-10			ISO 12815:2013 ~~ISO 12817:2013~~ ASTM D5961/D5961 M-13 ~~ASTM D6484/D6484 M-14~~			

present work the authors have preferred to differentiate both types of material, that is polymeric materials and polymer matrix composites, or what is the same, non-reinforced and reinforced polymeric materials.

As indicated above, Table 8 does not reflect the standards that, although identified in Forster's work, are ruled out as not applicable in the field of additive manufacturing. This is the case of ISO 14129:1997, which although it is identified in Forster's work, is considered not suitable for this manufacturing technology, in contrast to what is indicated in ISO 17296-3:2014, which identifies it as a standard for consultation.

Therefore, there are coincidences but also contradictions in the identification of consultation standards that the three standards consider and Forster's work offer. This way, Table 9 completes the information shown in Table 8, citing the corresponding consultation regulations in each case. In addition, three situations of special interest are identified using arrows of different colors.

- Green arrows: they draw attention to situations in which the same consultation standard is referred to in different standards on additive manufacturing or in Forster's work. Thus, standards that have a certain consensus regarding the four sources considered are identified.
- Red arrows: they identify situations in which a standard, identified as a valid reference in one of the sources, is rejected in another. This situation is consequence of Forster's work, which discards some standards that in a first approach can be defined as appropriate for the context of additive manufacturing.

TABLE 10. Identification of the regulations used for tensile testing in the main works consulted in this regard [53], [57], [61]–[77].

Tensile test		
Authors	Year	Standard used
Croccolo et al.	2013	ASTM D638
Torrado et al.	2014	ASTM D638
Tymrak et al.	2014	ASTM D638
Casavola et al.	2016	ASTM D638
Rankouhi et al.	2016	ASTM D638 ASTM D3039
Riddick et al.	2016	ASTM D638
Weng et al.	2016	ASTM D638
Alafaghani et al.	2017	ASTM D638
Cantrell et al.	2017	ASTM D638
Chacón et al.	2017	ASTM D638
Cwikla et al.	2017	ISO 527
Ferreira	2017	ASTM D638
Tanikella et al.	2017	ASTM D638
Zaldivar el al.	2017	ASTM D638
Aw et al.	2018	ASTM D638
Banjanin et al.	2018	ASTM D638
Kuznetsov et al.	2018	ASTM D638
Lubombo et al.	2018	ASTM D638
Akhoundi et al.	2019	ASTM D638
Liu et al.	2019	ASTM D638
Rajpurohit el al.	2019	ASTM D638

- Discontinuous black arrows: they identify standards applicable in different types of materials.

The third of these scenarios, is due in the case of ASTM 6272-10 and ASTM D790-10 standards to the already discussed consideration of polymer matrix composite materials as a type of polymeric materials or as an independent group. It draws much more attention in this regard that ISO 14129:1997, for shear test in fiber-reinforced plastic composites, is identified as a reference standard for ceramic materials in the field of additive manufacturing.

Table 9 is considered an interesting result of this work, as it constitutes a reference or guide to the relationship between the consultation standards called from the main general additive manufacturing standards, an also from Forster's work, which is considered another important reference in this field.

Many other works focused on the mechanical characterization of plastic parts obtained by additive processes were consulted, with special attention to FDM processes and tensile test, which are the most frequently used. As seen in Tables 4 and 8, polymers tensile test represents the only test for which the three additive manufacturing regulations identified call for consultation standards, and also the only test for which there is more than one reference in this regard, specifically two, ISO 527 and ASTM D638-14, as shown in Table 5.

Table 10 shows some of the main works consulted in this line, indicating the standards used in each case. A clear predominance of ASTM D638 can be observed as the reference chosen by the authors, except in the case of the work of Ćwikła *et al.* [57], In which the ISO 527 standard was used. This corrects the possible initial conclusion derived from the content of Table 5, which shows the identification of ISO 527 in the call for consultation by the three generic standards on additive manufacturing identified. However, Table 10 shows the preference that in practice most authors have by ASTM D638. This preference is also identified in previous review works [58], [59]. It is also possible to identify works of great interest in which similar studies are carried out without using any of these standards. For example, in the work developed by Webbe Kerekes *et al.* [60] a total of 30 dog-bone specimens were tested, bur their dimensions did not correspond to the ones defined in ISO 527 or ASTM D638-14.

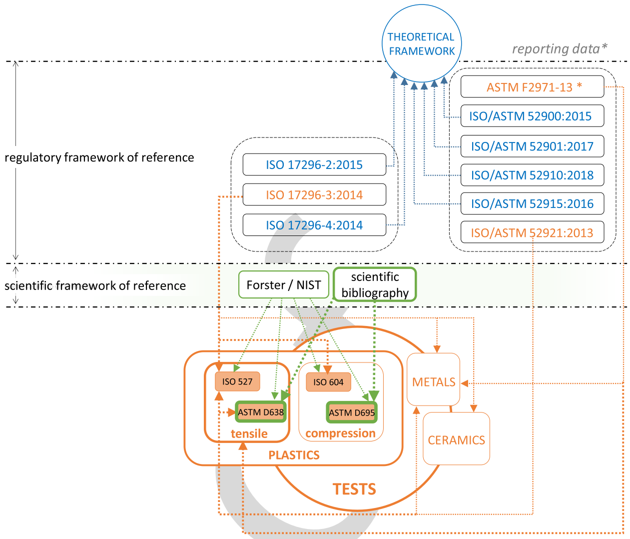


FIGURE 5. Identification of the standards for tensile and compression testing on plastic printed parts through the general standards on additive manufacturing and the scientific literature review carried out.

Fig. 5 resumes graphically the contribution of the standards on additive manufacturing and the scientific works consulted, in relation to the identification of standards that can serve as a reference for the mechanical test, specifically of traction and compression of polymeric parts obtained by additive manufacturing.

It can be seen that some of the standards on additive manufacturing considered contribute to the theoretical framework, this is the establishment of terms, definitions, etc.; and others to the identification of standards of application when different mechanical tests are carried out. As in the generic standards on additive manufacturing, the work developed by Forster consider these two standards as well as ISO 527 [44]–[48] and ISO 604 [49], for tensile and compression test respectively. So, research works identified in the review of the scientific production in this field are the ones which really allow to identify the standards ASTM D638-14 [50] and ASTM D695-15 [51], for tensile and compression test respectively, as the most used references.

Considering all of the above, the identification of ASTM D638 and ASTM D695 standards is considered justified as the main references to be taken into account in terms of tensile and compression tests of polymer parts obtained by additive manufacturing. The review carried out in this regard is considered useful given the lack of definition in some cases, and the contradictions in others, which have been revealed in relation to the regulations to be applied.

Other examples of the lack of consensus can be found consulting the information provided by filament manufacturers. In that sense, Table 11 shows the differences in the testing standards used by different FDM filament manufacturers when establishing tensile resistance values. Table 11 reflects what is stated in the technical data sheets of the products of three well-known companies that offer filaments for FDM printers. This information is available for download and consultation on the websites of these companies [78]–[80].

TABLE 11. Identification of regulations used by different filament manufacturers for FDM printers for tensile testing.

	PLA	ABS	PETG	NYLON	TPU, TPE	PC	PVA
BCN3D	ASTM D882	ISO 527	ISO 527	-	ISO37	-	ISO 527
STRATASYS	ASTM D638	ASTM D638	-	ASTM D638	-	ASTM D638	-
ULTIMAKER	ISO 527	ISO 527	-	ISO 527	ASTM D638	ISO 527	ISO 527

It can be seen that in addition to the standards previously identified as the main references for tensile test, ISO 527 and ASTM D638-14, other standards appear, such as ISO 37, typical of vulcanized elastomers, and ASTM D882, for thin sheets. And it can be observed a higher consideration of the ISO 527, in line with what is indicated in the general standards on additive manufacturing, but contrary to the trend observed in the review of the scientific works in this field.

But also, other situations highlight the lack of heterogeneity in the criteria. Aspects such as the orientation of the specimens during the printing process, the diameter of the nozzle used or the type and percentage of filling, are in some cases omitted and in others established without justifying the chosen values. Thus, it is possible to identify multiple examples that illustrate this lack of unity in the criteria to be considered. For example, the data sheets provided by BCN3D Technologies do not refer to the orientation of the specimen to be manufactured, the thickness of the nozzle or the filling. On the other hand, the XY orientation, the nozzle diameter of 0.4 mm and a filling of 90% are identified on the Ultimaker datasheets, without any of these decisions being justified. Other manufacturers, such as Ultrafuse [81], provide in their files a little more information in this regard, distinguishing for example the values obtained for three different orientations; and previously Infill3D offered datasheets considering two directions and different filling percentages, in this case 50% and 100%, which at least shows the influence of these aspects and makes a call to their consideration by users.

III. APPROACHES FAR FROM THE TRADITIONAL TEST STANDARDS

In the previous sections a review of the test standards referred from the general standards on additive manufacturing was made, and main differences and, in some cases contradictions, were pointed. Then, another review of the more common practices in this field was developed and the results of both are compared and exposed. And during this process a critical aspect has come up several times; the relative application that the traditional test standards for different materials have in the context of additive manufacturing. Many works has pointed this aspect [19], [21], [31] and two main approaches to the reasons can be distinguished.

On the one hand, the layer by layer forming process characteristic of additive manufacturing involves a lack of continuity in the material and anisotropic behavior. Thus, the application of the standards identified for mechanical testing, although it is possible, is strongly limited. In that sense, it would not be possible to speak of specimens that use filling patterns, but of solid specimens, in order to approximate as closely as possible to the conditions of the standards proposed as consultation documents. But, even so, the internal structure of adjacent filaments along successive layers introduces an evident discontinuity in the material, being able to identify clearly defined directions in the internal structure of the piece with different characteristics and mechanical responses. Fig. 6 and Fig.7 show different images of specimens for tensile test of FDM parts and allow to appreciate the commented situations.

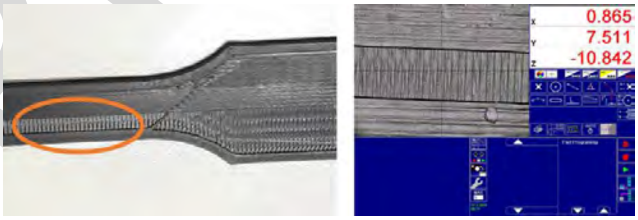


FIGURE 6. Unfinished specimen to allow the display of successive layers with perpendicular filament orientations in solid samples.

FIGURE 7. View of the cross section of two test specimen for tensile testing with horizontal position (left) and edgewise position (right). Images obtained by TESA-VISIO Digital Profile Projector.

On the other hand, the nature and the focus of many other works in this field demand approaches to the mechanical characterization of the pieces obtained which since the beginning are far from the framework defined by the standards on additive manufacturing. The infill structures usually used, and especially the complex interior structures that additive manufacturing allows, are examples of situations in which the materialization of pieces has nothing to do with continuous material approaches. And it is important to note that they are these new possibilities allowed by additive manufacturing, and impossible in traditional manufacturing contexts, which are being most intensively studied and improved by the scientific community and the industry. So, they are those scenarios in which the applicability of the test standards is more complicated and relative the ones in which exist more activity and the need of standards is higher. Fig. 8 resumes graphically this idea and the lack of applicability of the test standards referred to the level of isotropy and continuity of the material in the piece.

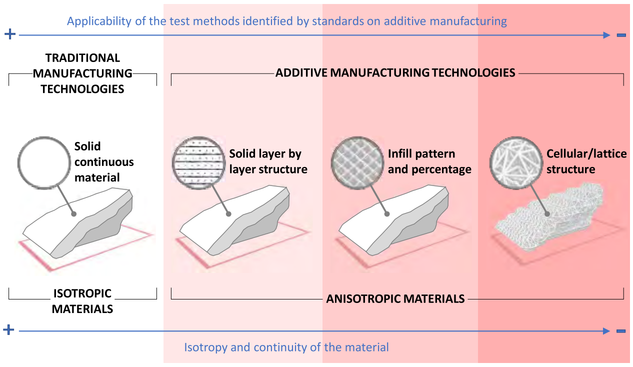


FIGURE 8. Applicability of the mechanical test standards identified in relation to the internal morphology of the parts obtained by additive manufacturing.

The use of cellular and lattice structures in the design of parts for additive manufacturing represent the most remote scenario in terms of applicability of the identified test standards. And in addition, these approaches have a great need of mechanical characterization, and are often linked to topology optimization analysis, of great importance in design for additive manufacturing. In these cases, the analysis of the mechanical resistance of the obtained parts can be oriented through the resistance of the cellular filling structures or the optimized structures established in the design rather than through the study of the material. These kind of approaches and the difficult applicability of testing standards in these contexts were deeply analyzed by the authors in previous works [21], [82].

Usually, the works developed from these kind of approaches, carry out the corresponding mechanical tests considering either the unit cells or small structures obtained as a sum of a certain number of them, but without referring the study to any testing standards and without using the defined specimens in them. The works developed by Chen *et al.* [83] and Hussein [84] illustrate the preparation of compression tests on cellular structures. In both cases, compression tests are carried out on the pieces considered without referring them to any testing standard and using own designed specimens, not standardized ones.

In addition, works in which the designs are based on lattice and cellular structures must consider not only particular cells in terms of mechanical response, but also the response obtained when the specific geometry of a particular design is built by adaptation of that initial and basic structure. So, it is common to find works that characterize the mechanical behavior of the pieces by testing parts of varied geometries which no correspond with standardized specimens [32], [85]–[89]. The variety of scenarios opened by additive manufacturing thanks to the geometric freedom that it allows, makes necessary much more specific standards in order to respond to particular needs of specific productive contexts. Zhang *et al.* identify some examples of this other group of standards on additive manufacturing, such as ASTM F2924-14, ASTM F3001-14, ASTM F3184-16 and ISO 13314:2011 [90]–[93]. The need of specific standards for particular productive scenarios and the efforts in this direction will be commented into the next section. In many of these works the analysis and the characterization of the tested parts combine the performance of mechanical tests in the laboratory and simulation work supported by the Finite Element Method (FEM). This approach allows to validate the results obtained in the simulations and characterize the mechanical behavior of the parts based on this type of structures [83], [86]–[89].

Some works have a special interest as examples of these kind of approaches since they address reviews of the state of the art from different points of view. For example, the work of Zhang *et al.* [32] is focused on cell structures for implant application, considering different technologies of additive manufacturing with metals and applying them in a particular material such as Ti-6Al-4V alloy, due to its biocompatibility. The mentioned work also incorporates in its review the geometry of the cell considered, compiling the results obtained by different authors for key parameters, such as the Elastic Module and the Elastic Limit. The work developed by Sing *et al.* [33] identifies different works oriented to the mechanical characterization of this type of structures under compression, traction, fatigue or flexion loads, and in this case obtained by SLM with different metallic materials. In that work cubic and cylindrical geometries are identified as the usual for the samples for compressive tests and also two standards are identified as possible references, ASTM E9 [94] and ISO 13314:2011 [93], which determines the compression test conditions for porous or cellular metallic materials.

Other works, as the one developed by Cooke *et al.* [34] identifies standards for different tests. Thus, for the tensile test, considers the ASTM C297 and ASTM C363 standards [95], [96], for compression the ASTM C364 [97], for shearing the ASTM C273 [98] and for bending the ASTM C393 [99]. All these standards have been developed by Committee D30.09, which is oriented to the study of materials of sandwich structure. As mentioned before, that type of materials would be closer to the nature of this type of geometries that additive technologies make possible, but they are not identified as references into the general standards on additive manufacturing.

IV. SPECIFIC REGULATORY DEVELOPMENTS. AN ALTERNATIVE APPROACH IN PROCESS

In this work the main standards on additive manufacturing have been identified, and from them, standards for mechanical test methods were identified. In addition, the most common practices in this field were also analyzed, and this allowed to pay special attention to some of them, since they are the most usually used by researchers. But, in general, the identification process resulted in very general standards not specific for polymeric materials nor for the corresponding manufacturing processes. The only exception in that regard is UNE-EN-ISO 116005:2012. But in any case, all these standards on additive manufacturing made reference to general standards for mechanical testing of polymers. In no case specific standards or methods for mechanical testing of parts obtained by additive manufacturing were identified.

In this section the search of standards on additive manufacturing is expanded and a significant number of specific standards, both for particular materials and processes, are included in the review. Table 12 shows the identified standards on additive manufacturing developed by ASTM International. The information provided in each case includes the code and full description, the year of publication, the committee and subcommittee responsible for their development and contents.

Then two different technological approach are differentiated. On the one hand, standards developed for additive technologies from a global point of view. And, on the other hand, standards focused on particular additive technologies and processes. And, also the material referred in each standard is considered, differentiating between metals and polymers, the two most important groups of materials used in AM. When the standards are not developed for a particular category of material or for a specific one, no material is indicated. In that sense, it must be commented that ceramics are not considered on Table 12, since it was not possible to identify standards focused in this type of materials, so only the general standards could be referred to them in the table. In that context it was considered more appropriate not to include them in the table.

On the left side of the table, the analysis is carried out for all the standards developed over time by ASTM International in this field. On the right side, new columns are added, and the same analysis is shown, but this time considering only the active standards. Thus, the columns on the left show the evolution of these standards, and the ones on the right resume the actual context.

As can be seen, standards usually evolve through the publication of new versions or revisions which replace the previous ones, but the main code and basic description remains. In a few cases (mainly related to general approaches) standards are withdrawn. This is the case of ASTM F2915 and ASTM F2921; the first one was centered in defining the standard specification for file formats used in AM and the second one in describing important aspects about the coordinate systems and tests methodologies; the new standards replacing those ones are ASTM 52915 (published in 2020) and ISO/ASTM 52921 (published in 2013) respectively. The only standard with a specific approach that has been withdrawn and replaced is ASTM F3303 [110]; the new standard, ISO/ASTM 52904, has been published in 2019 and is focused on describing good practices to meet critical applications in metal powder bed fusion processes such as commercial aerospace components and medical implants. The case of ASTM F3303, replaced by ISO/ASTM 52904, illustrates one of the reasons why some standards are withdrawn. As exposed on ASTM International Web Site, the common goal of both organizations, the ISO and ASTM International, of approving single standards used by all motivates the replacement of documents initially developed by one of the organizations by versions reviewed and approved by both of them. The case of ASTM F2792-12a is different, since this standard is withdrawn but not replaced.

The rest standards in Table 12 are mainly specific standards of recent development (the oldest one is from 2011) and they have experience a fast evolution that can be observed by the number of new versions in a very short period of time (in some cases such as the ASTM F3055, three versions in the same year). Most of these standards have been developed for the category powder bed fusion with different metallic alloys such as nickel alloys [102], [103], titanium alloys [90], [91], [109], cobalt alloy [107], aluminum alloy [111], stainless steel [92]; and plastic materials [104]; and more recently specialized in laser - based powder bed fusion of metals [117] and polymers [118]. Importance of directed energy deposition category is also shown through the standard ASTM F3187-16 [106] and more recently, the publication of the new standard ISO/ASTM 52922 [120] in 2019. Interest in material extrusion of plastics has arisen as well, as we can see through the publication of the new standard ISO/ASTM 52903 [114] in 2020.

From the information shown in Table 12, different analysis can be made. Fig. 9 shows the different productivity in terms of active standards of the different subcommittees within the ASTM International Committee F42 on Additive Manufacturing. Both the number of standards and the percentage that in each case they represent of the total of standards are indicated. In the left side of Fig. 8 the distribution of the standards developed over time is shown. The graph on the right considers only the currently active standards. Thus, as in Table 12, the first information provides an approximation to the activity of these committees in terms of elaboration and promotion of new standards during the last years, and the second gives a visual of their weight within the actual set of active standards on additive manufacturing.

As it can be seen in the graph, the standards developed by subcommittee F42.05 on Materials and Processes represent half of the total of standards developed in the graph on the left and the 65% in the graph of the right. Thus, it is the Subcommittee F42.05 on Materials and Processes the one with the highest number of contributions to the collection of standards developed. And, within that group, it is also remarkable the great dominance of standards focused on metals, in comparison to polymers or ceramics. In fact, it must be noticed that the only item for ceramics corresponds in Table 12 to ISO/ASTM 52901-16, which adds an entry for each material since it makes a general approach not focused

TABLE 12. Development, evolution and actual context of standards on additive manufacturing by ASTM International in the last decade [39]–[43], [90]–[92], [100]–[122].

CODE	CODE & FULL DESCRIPTION	YEAR			F42.05 Mat. & Proc.				F42.07 Applications										F42.90 Exec.					TECH. APPROACH		MATERIAL		STATE		TECH. APPROACH		MATERIAL	
			F42.01 Test Methods	F42.04 Design	.01 Metals	.02 Polymers	.03 Ceramics	F42.06 Environ., Health & Safety	.01 Aviation	.02 Spaceflight	.03 Medical/Bio.	.04 Transp./H. Mach.	.05 Maritime	.06 Electronics	.07 Construction	.08 Oil/Gas	.09 Consumer	F42.08 Data	.01 Strategic Plan.	.02 Awards	.03 Research & Inn.	F42.91 Terminology	F42.95 US TAG to ISO TC 261	General	Specific	Metal	Polymer		Active standard	General	Specific	Metal	Polymer
ASTM F2792 - 09	ASTM F2792 - 09 Standard Terminology for Additive Manufacturing Technologies	2009																				■		■		-	-	Superseded	no replacement (*ISO/ASTM 52900)				
ASTM F2792 - 09e1	ASTM F2792 - 09e1 Standard Terminology for Additive Manufacturing Technologies	2009																				■		■		-	-	Superseded					
ASTM F2792 - 10	ASTM F2792 - 10 Standard Terminology for Additive Manufacturing Technologies	2010																				■		■		-	-	Superseded					
ASTM F2792 - 10e1	ASTM F2792 - 10e1 Standard Terminology for Additive Manufacturing Technologies	2010																				■		■		-	-	Superseded					
ASTM F2792 - 12	ASTM F2792 - 12 Standard Terminology for Additive Manufacturing Technologies,	2012																				■		■		-	-	Superseded					
ASTM F2792 - 12a	ASTM F2792 - 12a Standard Terminology for Additive Manufacturing Technologies, (Withdrawn 2015)	2012																				■		■		-	-	Withdrawn					
ASTM F2915 - 11	ASTM F2915 - 11 Standard Specification for Additive Manufacturing File Format (AMF)	2011		■																				■		-	-	Superseded	ASTM 52915				
ASTM F2915 - 12	ASTM F2915 - 12 Standard Specification for Additive Manufacturing File Format (AMF) Version 1.1 (Withdrawn 2013)	2012		■																				■		-	-	Withdrawn					
ASTM F2921 - 11	ASTM F2921 - 11 Standard Terminology for Additive ManufacturingCoordinate Systems and Test Methodologies	2011	■																					■		-	-	Superseded	ISO/ASTM 52921				
ASTM F2921 - 11e1	ASTM F2921 - 11e1 Standard Terminology for Additive Manufacturing—Coordinate Systems and Test Methodologies	2011	■																					■		-	-	Superseded					
ASTM F2921 - 11e2	ASTM F2921 - 11e2 Standard Terminology for Additive Manufacturing—Coordinate Systems and Test Methodologies	2011	■																					■		-	-	Superseded					
ASTM F2921 - 11e3	ASTM F2921 - 11e3 Standard Terminology for Additive Manufacturing—Coordinate Systems and Test Methodologies (Withdrawn 2013)	2011	■																					■		-	-	Withdrawn					
ASTM F2924 - 12	ASTM F2924 - 12 Standard Specification for Additive Manufacturing Titanium-6 Aluminum-4 Vanadium with Powder Bed Fusion	2011			■																				■	■		Superseded	ASTM F2924 - 14		■	■	
ASTM F2924 - 12a	ASTM F2924 - 12a Standard Specification for Additive Manufacturing Titanium-6 Aluminum-4 Vanadium with Powder Bed Fusion	2012			■																				■	■		Superseded					
ASTM F2924 - 14	ASTM F2924-14 Standard Specification for Additive Manufacturing Titanium-6 Aluminum-4 Vanadium with Powder Bed Fusion	2014			■																				■	■		Active					
ASTM F2971 - 13	ASTM F2971-13 Standard Practice for Reporting Data for Test Specimens Prepared by Additive Manufacturing	2013	■																					■		-	-	Active	ASTM F2971 - 13	■		-	-
ASTM F3001 - 13	ASTM F3001 - 13 Standard Specification for Additive Manufacturing Titanium-6 Aluminum-4 Vanadium ELI (Extra Low Interstitial) with Powder Bed Fusion	2013			■																				■	■		Superseded	ASTM F3001 - 14		■	■	
ASTM F3001 - 14	ASTM F3001-14 Standard Specification for Additive Manufacturing Titanium-6 Aluminum-4 Vanadium ELI (Extra Low Interstitial) with Powder Bed Fusion	2014			■																				■	■		Active					
ASTM F3049 - 14	ASTM F3049-14 Standard Guide for Characterizing Properties of Metal Powders Used for Additive Manufacturing Processes	2014			■																				■	■		Active	ASTM F3049 - 14		■	■	
ASTM F3055 - 14	ASTM F3055 - 14 Standard Specification for Additive Manufacturing Nickel Alloy (UNS N07718) with Powder Bed Fusion	2014			■																				■	■		Superseded	ASTM F3055 - 14a		■	■	
ASTM F3055 - 14e1	ASTM F3055 - 14e1 Standard Specification for Additive Manufacturing Nickel Alloy (UNS N07718) with Powder Bed Fusion	2014			■																				■	■		Superseded					
ASTM F3055 - 14a	ASTM F3055-14a Standard Specification for Additive Manufacturing Nickel Alloy (UNS N07718) with Powder Bed Fusion	2014			■																				■	■		Active					
ASTM F3056 - 14	ASTM F3056 - 14 Standard Specification for Additive Manufacturing Nickel Alloy (UNS N06625) with Powder Bed Fusion	2014			■																				■	■		Superseded	ASTM F3056 - 14e1		■	■	
ASTM F3056 - 14e1	ASTM F3056-14e1 Standard Specification for Additive Manufacturing Nickel Alloy (UNS N06625) with Powder Bed Fusion	2014			■																				■	■		Active					
ASTM F3091 - F3091M	ASTM F3091/F3091M-14 Standard Specification for Powder Bed Fusion of Plastic Materials	2014				■																			■		■	Active	ASTM F3091 - F3091M		■		■
ASTM F3122 - 14	ASTM F3122-14 Standard Guide for Evaluating Mechanical Properties of Metal Materials Made via Additive Manufacturing Processes	2014	■																						■	■		Active	ASTM F3122 - 14		■	■	
ASTM F3184 - 16	ASTM F3184-16 Standard Specification for Additive Manufacturing Stainless Steel Alloy (UNS S31603) with Powder Bed Fusion	2016			■																				■	■		Active	ASTM F3184 - 16		■	■	
ASTM F3187 - 16	ASTM F3187-16 Standard Guide for Directed Energy Deposition of Metals	2016			■																				■	■		Active	ASTM F3187 - 16		■	■	
ASTM F3213 - 17	ASTM F3213-17 Standard for Additive Manufacturing — Finished Part Properties — Standard Specification for Cobalt-28 Chromium-6 Molybdenum via Powder Bed Fusion	2017			■																				■	■		Active	ASTM F3213 - 17		■	■	
ASTM F3301 - 18	ASTM F3301 - 18 Standard for Additive Manufacturing – Post Processing Methods – Standard Specification for Thermal Post-Processing Metal Parts Made Via Powder Bed Fusion	2018			■																				■	■		Superseded	ASTM F3301 - 18a		■	■	
ASTM F3301 - 18a	ASTM F3301-18a Standard for Additive Manufacturing — Post Processing Methods — Standard Specification for Thermal Post-Processing Metal Parts Made Via Powder Bed Fusion1, 2	2018			■																				■	■		Active					
ASTM F3302 - 18	ASTM F3302-18 Standard for Additive Manufacturing — Finished Part Properties — Standard Specification for Titanium Alloys via Powder Bed Fusion	2018			■																				■	■		Active	ASTM F3302 - 18		■	■	
ASTM F3303 - 18	ASTM F3303-18 Standard for Additive Manufacturing — Process Characteristics and Performance: Practice for Metal Powder Bed Fusion Process to Meet Critical Applications	2018			■																				■	■		Withdrawn	ISO/ASTM 52904-19				
ASTM F3318 - 18	ASTM F3318-18 Standard for Additive Manufacturing — Finished Part Properties — Specification for AlSi10Mg with Powder Bed Fusion — Laser Beam	2018			■																				■	■		Active	ASTM F3318 - 18		■	■	
ASTM F3335 - 20	ASTM F3335 - 20 Standard Guide for Assessing the Removal of Additive Manufacturing Residues in Medical Devices Fabricated by Powder Bed Fusion	2020	**F04 Medical and Surgical Materials & Devices** (.15 Material Test Methods)																						■	■		Active	ASTM F3335 - 20		■	■	
ISO / ASTM 52900 - 15	ISO / ASTM52900 - 15 Standard Terminology for Additive Manufacturing – General Principles – Terminology	2015																				■		■		-	-	Active	ISO ASTM 52900 - 15	■		-	-
ISO / ASTM 52901 - 16	ISO / ASTM52901 - 16 Standard Guide for Additive Manufacturing – General Principles – Requirements for Purchased AM Parts	2016			■	■	■																	■		-	-	Active	ISO ASTM 52901 - 16	■		-	-
ISO / ASTM 52902 - 19	ASTM ISO/ASTM52902-19 Additive manufacturing — Test artifacts — Geometric capability assessment of additive manufacturing systems	2019	■																						■		■	Active	ISO / ASTM 52902 - 19		■		■
ISO / ASTM 52903 - 20	ISO / ASTM52903 - 20 Additive manufacturing — Material extrusion-based additive manufacturing of plastic materials — Part 1: Feedstock materials	2020				■																			■		■	Active	ISO / ASTM 52903 - 20		■		■
ISO / ASTM 52904 - 19	ISO / ASTM52904 - 19 Additive Manufacturing – Process Characteristics and Performance: Practice for Metal Powder Bed Fusion Process to Meet Critical Applications	2019			■																				■	■		Active	ISO / ASTM 52904 - 19		■	■	
ISO / ASTM 52907 - 19	ISO/ASTM52907-19 Additive manufacturing — Feedstock materials — Methods to	2019	■																						■	■		Active	ISO / ASTM 52907 - 19		■	■	
ISO / ASTM 52910 - 17	ISO / ASTM52910 - 17 Standard Guidelines for Design for Additive Manufacturing	2017		■																				■		-	-	Superseded	ISO ASTM 52910 - 18	■		-	-
ISO / ASTM 52910 - 18	ISO / ASTM52910 - 18 Additive manufacturing — Design — Requirements, guidelines and recommendations	2018		■																				■		-	-	Active					
ISO / ASTM 52911-1-19	ISO/ASTM52911-1-19 Additive manufacturing — Design — Part 1: Laser-based powder bed fusion of metals	2019		■																					■	■		Active	ISO / ASTM 52911-1-19		■	■	
ISO / ASTM 52911-2-19	ISO/ASTM52911-2-19 Additive manufacturing — Design — Part 2: Laser-based powder bed fusion of polymers	2019		■																					■		■	Active	ISO / ASTM 52911-2-19		■		■
ISO / ASTM 52922-19	ISO/ASTM52922-19 Guide for Additive Manufacturing — Design — Directed Energy Deposition	2019		■																					■	■		Active	ISO / ASTM 52922-19		■	■	
ISO / ASTM 52915 - 13	ISO / ASTM52915 - 13 Standard Specification for Additive Manufacturing File Format (AMF) Version 1.1	2013		■																				■		-	-	Superseded	ISO ASTM 52915 - 16	■		-	-
ISO / ASTM 52915 - 16	ISO / ASTM52915 - 16 Standard Specification for Additive Manufacturing File Format (AMF) Version 1.2	2016		■																				■		-	-	Active					
ISO / ASTM 52921 - 13	ISO/ASTM52921-13 Standard Terminology for Additive Manufacturing—Coordinate Systems and Test Methodologies	2013	■																					■		-	-	Active	ISO / ASTM 52921 - 13(2019)	■		-	-

in any material category, so it cannot be ignored, but it must account for all.

Considering the subcommittees with entries in Fig. 9, Fig. 10 differentiates in each case the number of standards developed from general approaches and applicable to any additive technology and the ones which are specific for any process. It can be seen a strong trend to specific standards in the case of subcommittee F42.05 on Materials and Processes, what is logical and consistent with its own nature.

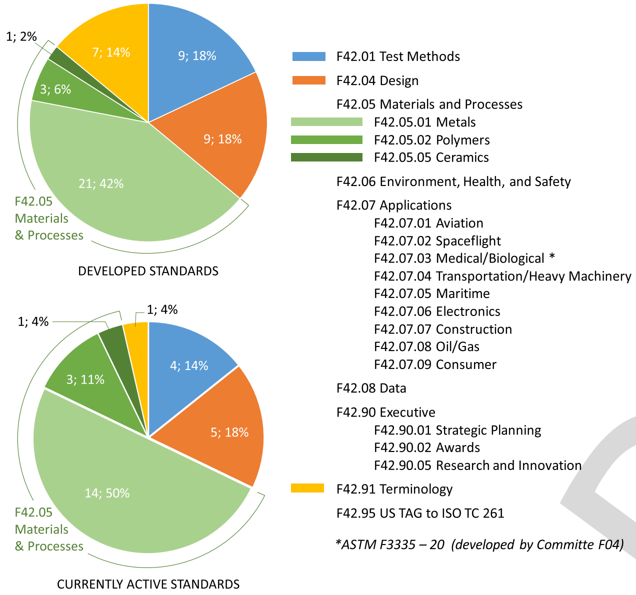


FIGURE 9. **Standards developed by the different subcommittees within the committee F42 on Additive Manufacturing Technologies: standards developed over time (left) and active standards (right).**

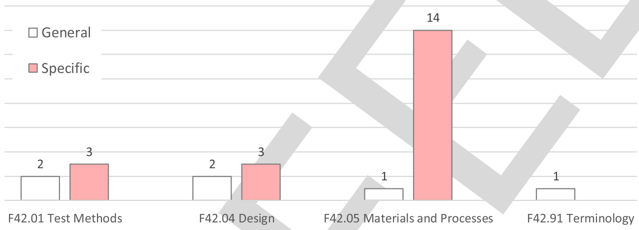


FIGURE 10. **General and specific technological approaches for the standards developed by the different subcommittees.**

Fig. 11 tries to show in a matrix classification system the most and the less common approaches within the collection of standards on additive manufacturing identified. The intersections between columns and rows groups of standards with similar approaches both from technological and material perspectives. General standards are represented without background color and dashed line, since they must be considered in the count of the general standards, but only once, and they must be ignored when material is considered, because both metals and polymers are referred in them.

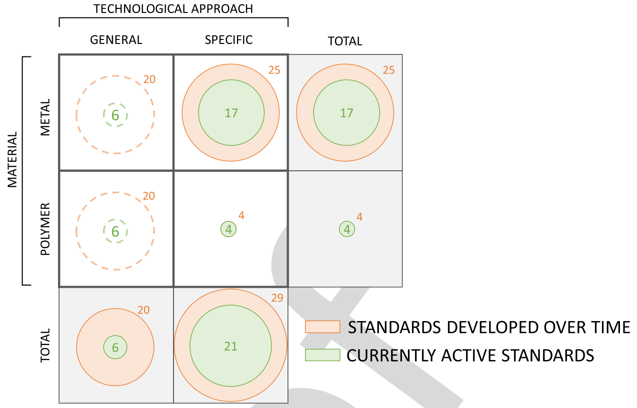


FIGURE 11. **Matrix classification of standards on additive manufacturing considering both the technological approach and the material.**

All these graphs show a great effort focused on the development of specific standards to be applied to particular contexts defined by the characteristics of particular materials and/or the critical aspects of specific processes. Thus, these specific approaches represent the main standardization strategy for additive manufacturing processes and products. In that sense, as part of the information provided in the website of the committee F42 on Additive Manufacturing, the schema of the AM Standards Structure provided is considered specially interesting and clarifying. Three main groups or levels of standards are identified based on the degree of specialization or specificity. Thus, first, a top level of general standards is identified, focused on aspects such as terminology, data formats, design guidelines, test methods or safety among others, and all them from general and transversal points of view. Then two levels of higher specialization are considered. First in relation to specific categories of materials or processes and then focused on specific materials or processes. And through these three levels, three approaches are identified: feedstock materials, processes/equipment and finished parts. On the other hand, the schema allows to identify standards about test methods in two levels within the structure. First, in the top-level of general standards. And also, in the next level, relative to categories of materials or processes and referred to finished parts.

From the mentioned schema, Fig. 12 tries to locate each currently active standard identified in Table 12 in the corresponding place within the structure. This is interesting since the structure shows the strategy designed for the development of a collection of standards on additive manufacturing, and Fig. 12 provides an image of the current situation. In each case the corresponding subcommittee is also identified. And when it exists an approach to a specific material or material category, this aspect is included too. Thus, general standards, which are not focused on a particular material or material category, do not include this information, but in other standards a P or an M are indicated, as indications of polymer and metallic materials.

Not in all cases the location of the standards within the structure was clear. ISO/ASTM 52911-1-19 [117] and ISO/ASTM 52911-2-19 [118] differentiate between polymer

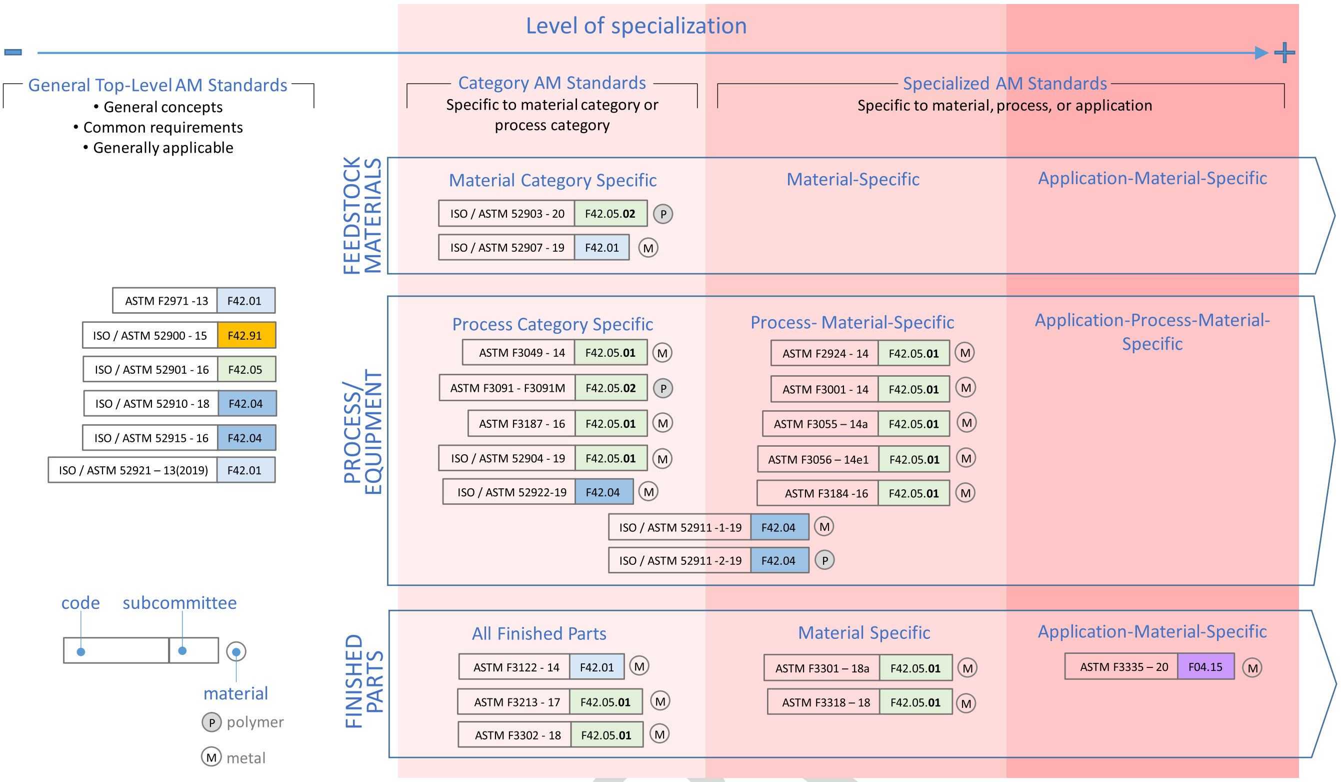


FIGURE 12. **Applicability of the mechanical test standards identified in relation to the internal morphology of the parts obtained by additive manufacturing.**

and metallic materials as if it happens in other cases. Thus, it exists certain level of concretion, but categories are indicated, no specific metals or polymers, so these two standards are shown between two areas. It is also remarkable that the only standard identified during the review classifiable in the right column of Fig. 11 referred to applications is the standard ASTM F3335-20 [112], which was not developed by Committee F42. It was developed by Committee F04 on Medical and Surgical Materials & Devices, concretely by the subcommittee F04.15 on Material Test Methods.

The review of all these normative developments also reveals a lack of specific references, similar to the ones developed for certain metals or for other material categories, such as polymers. Considering the recurring applicability problems identified for the standards used to carry out mechanical tests on parts obtained by additive manufacturing using polymeric materials, it seems logical to follow a similar strategy of specialization for these materials and their processes. The particularities and differences of additive technologies compared to other manufacturing processes also exist between themselves. The construction process layer by layer defines a clear border with other manufacturing technologies. But this border only affects transversally all these additive technologies regarding the geometric freedom they allow. After, it is possible to identify significant differences between them considering the nature and characteristics of the layers they define and also to the relation and cohesion between adjacent layers. So, apart from general aspects as terminology or main concepts, it is difficult to face aspects such as the mechanical characterization of the obtained products from perspectives common to different additive technologies.

V. CONCLUSIONS

In this work, a thorough review of the main general and specific regulatory developments in materials and design standards for additive manufacturing has been carried out, with special attention to the standards for mechanical characterization of obtained products. One of the main contributions of this work is that the analysis developed allow to identify some weak points, or at least not defined enough, in the current additive manufacturing standardization landscape; the identification process of standards for mechanical test methods resulted in very general standards not specific for materials nor for the corresponding manufacturing processes.

Another important conclusion is that a trend through the development of specific standards for particular additive processes and materials is identified; so, the key for next regulatory developments in mechanical testing is to develop standards that take into account particular AM processes and materials, as in the case of regulatory developments for additive manufacturing of specific alloys and process categories already developed and commented in this work. That specialization strategy appears probably as the most appropriate alternative to face the identified weakness. So, it could be said that currently standardization on additive manufacturing presents an incomplete framework, but one in the right direction.

As a practical contribution of the paper, the proposed approaches and results obtained provide main guidelines for researchers, engineers, designers and makers to understand and use the current standardization structure on additive manufacturing within their particular contexts with the current framework. And, also an overview of standardization on additive manufacturing and a prospective interpretation of the faced approaches in this work is presented.

And finally, it can be said that, in that sense, a great gap between available standard about additive technologies based on metallic materials and polymer materials has raised during the last years. The huge potential of additive manufacturing with metals in many industrial sectors is an evidence. But it should be noted the importance of the wide variety of solutions available for additive manufacturing with polymeric materials, such as desktop 3D printers. Access to this equipment is more and more common. Designer, maker and consumer can be the same person, and standardization on additive manufacturing must also ensure the quality and safety of the products obtained in those other scenarios. Crisis as the one caused by COVID-19 reveal the potential and capacity of this alternative productive structure when working with a common goal, and also the need of a clear regulatory framework for the obtained products. So new standardization developments with the proposed approach are a challenge to face in the next years.

REFERENCES

[1] I. Gibson, D. W. Rosen, and B. Stucker, *Additive Manufacturing Technologies: Rapid Prototyping to Direct Digital Manufacturing*. Boston, MA, USA: Springer, 2010.

[2] J.-Y. Lee, J. An, and C. K. Chua, "Fundamentals and applications of 3D printing for novel materials," *Appl. Mater. Today*, vol. 7, pp. 120–133, Jun. 2017, doi: 10.1016/j.apmt.2017.02.004.

[3] N. van de Werken, H. Tekinalp, P. Khanbolouki, S. Ozcan, A. Williams, and M. Tehrani, "Additively manufactured carbon fiber-reinforced composites: State of the art and perspective," *Additive Manuf.*, vol. 31, Jan. 2020, Art. no. 100962, doi: 10.1016/j.addma.2019.100962.

[4] A. Rodríguez-Prieto, A. M. Camacho, A. M. Aragón, M. A. Sebastián, and A. Yanguas-Gil, "Polymers selection for harsh environments to be processed using additive manufacturing techniques," *IEEE Access*, vol. 6, pp. 29899–29911, 2018, doi: 10.1109/ACCESS.2018.2844360.

[5] A. Paolini, S. Kollmannsberger, and E. Rank, "Additive manufacturing in construction: A review on processes, applications, and digital planning methods," *Additive Manuf.*, vol. 30, Dec. 2019, Art. no. 100894, doi: 10.1016/j.addma.2019.100894.

[6] K. Johnson, M. Zemba, B. P. Conner, J. Walker, E. Burden, K. Rogers, K. R. Cwiok, E. Macdonald, and P. Cortes, "Digital manufacturing of pathologically-complex 3D printed antennas," *IEEE Access*, vol. 7, pp. 39378–39389, 2019, doi: 10.1109/ACCESS.2019.2906868.

[7] S. A. M. Tofail, E. P. Koumoulos, A. Bandyopadhyay, S. Bose, L. O'Donoghue, and C. Charitidis, "Additive manufacturing: Scientific and technological challenges, market uptake and opportunities," *Mater. Today*, vol. 21, no. 1, pp. 22–37, Jan. 2018, doi: 10.1016/j.mattod.2017.07.001.

[8] O. Abdulhameed, A. Al-Ahmari, W. Ameen, and S. H. Mian, "Additive manufacturing: Challenges, trends, and applications," *Adv. Mech. Eng.*, vol. 11, no. 2, pp. 1–27, 2019, doi: 10.1177/1687814018822880.

[9] M. Attaran, "The rise of 3-D printing: The advantages of additive manufacturing over traditional manufacturing," *Bus. Horizons*, vol. 60, no. 5, pp. 677–688, Sep. 2017, doi: 10.1016/j.bushor.2017.05.011.

[10] M. Pérez-Pérez, E. Gómez, and M. Sebastián, "Delphi prospection on additive manufacturing in 2030: Implications for education and employment in spain," *Materials*, vol. 11, no. 9, p. 1500, Aug. 2018, doi: 10.3390/ma11091500.

[11] H.-S. Yoon, J.-Y. Lee, H.-S. Kim, M.-S. Kim, E.-S. Kim, Y.-J. Shin, W.-S. Chu, and S.-H. Ahn, "A comparison of energy consumption in bulk forming, subtractive, and additive processes: Review and case study," *Int. J. Precis. Eng. Manufacturing-Green Technol.*, vol. 1, no. 3, pp. 261–279, Jul. 2014, doi: 10.1007/s40684-014-0033-0.

[12] G. Costabile, M. Fera, F. Fruggiero, A. Lambiase, and D. Pham, "Cost models of additive manufacturing: A literature review," *Int. J. Ind. Eng. Comput.*, vol. 8, no. 2, pp. 263–282, 2016, doi: 10.5267/j.ijiec.2016.9.001.

[13] S. Ford and M. Despeisse, "Additive manufacturing and sustainability: An exploratory study of the advantages and challenges," *J. Cleaner Prod.*, vol. 137, pp. 1573–1587, Nov. 2016, doi: 10.1016/j.jclepro.2016.04.150.

[14] L. M. G. Graves, J. Lubell, W. King, and M. Yampolskiy, "Characteristic aspects of additive manufacturing security from security awareness perspectives," *IEEE Access*, vol. 7, pp. 103833–103853, 2019, doi: 10.1109/ACCESS.2019.2931738.

[15] S. Chong, G.-T. Pan, J. Chin, P. Show, T. Yang, and C.-M. Huang, "Integration of 3D printing and industry 4.0 into engineering teaching," *Sustainability*, vol. 10, no. 11, p. 3960, Oct. 2018, doi: 10.3390/su10113960.

[16] S. Ford and T. Minshall, "Invited review article: Where and how 3D printing is used in teaching and education," *Additive Manuf.*, vol. 25, pp. 131–150, Jan. 2019, doi: 10.1016/j.addma.2018.10.028.

[17] H.-C. Yang, M. Adnan, C.-H. Huang, F.-T. Cheng, Y.-L. Lo, and C.-H. Hsu, "An intelligent metrology architecture with AVM for metal additive manufacturing," *IEEE Robot. Autom. Lett.*, vol. 4, no. 3, pp. 2886–2893, Jul. 2019, doi: 10.1109/LRA.2019.2921927.

[18] A. Rodriguez-Prieto, A. Aragon, A. M. Camacho, and M. Sebastian, "Analysis of the current scenario of additive manufacturing standardization and certification," in *Proc. 22nd Int. Congr. Project Manage. Eng.*, Madrid, Spain, Jul. 2018, pp. 1011–1023. [Online]. Available: https://www.researchgate.net/publication/326405459_Analysis_of_the_current_scenario_of_additive_manufacturing_standardization_and_certification

[19] A. M. Forster, "Materials testing standards for additive manufacturing of polymer materials: State of the art and standards applicability," *Addit. Manuf. Mater. Stand. Test. Appl.*, pp. 67–123, 2015. AQ:4

[20] A. Rodríguez-Panes, J. Claver, A. M. Camacho, and M. Sebastián, "Análisis normativo y evaluación geométrica de probetas para la caracterización mecánica de piezas obtenidas por fabricación aditiva mediante FDM," in *Proc. 22th Nat. Congr. Mech. Eng.*, Sep. 2018, pp. 1–11.

[21] A. García-Domínguez, J. Claver, A. M. Camacho, and M. A. Sebastián, "Considerations on the applicability of test methods for mechanical characterization of materials manufactured by FDM," *Materials*, vol. 13, no. 1, p. 28, Dec. 2019, doi: 10.3390/ma13010028.

[22] C. Atkinson, "G20 leaders must answer to COVID-19," *Science*, vol. 368, no. 6487, p. 111, 2020, doi: 10.1126/science.abc1025.

[23] D. Ivanov and A. Dolgui, "Viability of intertwined supply networks: Extending the supply chain resilience angles towards survivability. A position paper motivated by COVID-19 outbreak," *Int. J. Prod. Res.*, vol. 58, no. 10, pp. 1–12, 2020, doi: 10.1080/00207543.2020.1750727.

[24] L. Cavallo, A. Marcianò, M. Cicciù, and G. Oteri, "3D printing beyond dentistry during COVID 19 epidemic: A technical note for producing connectors to breathing devices," *Prosthesis*, vol. 2, no. 2, pp. 46–52, Apr. 2020, doi: 10.3390/prosthesis2020005.

[25] A. Mostaghimi, M.-J. Antonini, D. Plana, P. D. Anderson, B. Beller, E. W. Boyer, A. Fannin, J. Freake, R. Oakley, M. S. Sinha, L. Smith, C. Van, H. Yang, P. Sorger, N. R. LeBoeuf, and S. H. Yu, "Rapid prototyping and clinical testing of a reusable face shield for health care workers responding to the COVID-19 pandemic," *medRxiv:2020.04.11.20061960*, 2020, doi: 10.1101/2020.04.11.20061960. AQ:5

[26] A. L. Clarke, "3D printed circuit splitter and flow restriction devices for multiple patient lung ventilation using one anaesthesia workstation or ventilator," *Anaesthesia*, vol. 75, no. 6, pp. 819–820, vol. 2020, doi: 10.1111/anae.15063.

[27] J. M. Zuniga and A. Cortes, "The role of additive manufacturing and antimicrobial polymers in the COVID-19 pandemic," *Expert Rev. Med. Devices*, vol. 17, no. 6, pp. 477–481, Jun. 2020, doi: 10.1080/17434440.2020.1756771.

[28] J. M. Pearce, "A review of open source ventilators for COVID-19 and future pandemics," *FResearch*, vol. 9, p. 218, Mar. 2020, doi: 10.12688/f1000research.22942.1.

[29] R. Tino, R. Moore, S. Antoline, P. Ravi, N. Wake, C. N. Ionita, J. M. Morris, S. J. Decker, A. Sheikh, F. J. Rybicki, and L. L. Chepelev, "COVID-19 and the role of 3D printing in medicine," *3D Printing Med.*, vol. 6, pp. 1–8, Apr. 2020.

[30] C. Pandemic, S. Pieralli, T. Fretwurst, J. Nold, K. Nelson, R. Schmelzeisen, E. Hellwig, and B. C. Spies, "3-D printed protective equipment during COVID-19 pandemic," *Materials*, vol. 7, no. 8, p. 1997, Jan. 2020.

[31] A. Rodríguez-Panes, J. Claver, and A. Camacho, "The influence of manufacturing parameters on the mechanical behaviour of PLA and ABS pieces manufactured by FDM: A comparative analysis," *Materials*, vol. 11, no. 8, p. 1333, Aug. 2018, doi: 10.3390/ma11081333.

[32] X.-Y. Zhang, G. Fang, and J. Zhou, "Additively manufactured scaffolds for bone tissue engineering and the prediction of their mechanical behavior: A review," *Materials*, vol. 10, no. 1, p. 50, Jan. 2017, doi: 10.3390/ma10010050.

[33] S. L. Sing, Y. Miao, F. E. Wiria, and W. Y. Yeong, "Manufacturability and mechanical testing considerations of metallic scaffolds fabricated using selective laser melting: A review," *Biomed. Sci. Eng.*, vol. 2, May 2016, doi: 10.4081/bse.2016.11.

[34] *An Investigation of the Material Properties of Laser Sintered*, S Corp., S Corp., pp. 908–928. AQ:6

[35] *Additive Manufacturing General Principles. Part 2: Overview of Process Categories and Raw Materials*, document ISO 17296-2:2015, International Organization for Standardization, Geneva, Switzerland, 2015.

[36] *Additive Manufacturing—General Principles—Part 3: Main Characteristics and Corresponding Test Methods*, document ISO 17296-3:2014, International Organization for Standardization, Geneva, Switzerland, 2014.

[37] *Fabricación Por adición de Capas en Materiales Plásticos. Fabricación Aditiva. Preparación de Probetas*, document AENOR/UNE 116005, AENOR, Madrid, Spain, 2012.

[38] *Additive Manufacturing General Principles—Part 4: Overview of Data Exchange*, Standard ISO 17296-4:2014, International Organization for Standardization, Geneva, Switzerland, 2014.

[39] *Additive Manufacturing—General Principles—Terminology International Organization for Standardization*, document ISO/ASTM 52900:2015, Geneva, Switzerland, 2015.

[40] *Additive Manufacturing—General Principles—Requirements for Purchased AM Parts*, document ISO/ASTM 52901:2017, International Organization for Standardization, Geneva, Switzerland, 2017.

[41] *Additive Manufacturing—Design—Requirements, Guidelines and Recommendations*, document ISO/ASTM 52910:2018, International Organization for Standardization, Geneva, Switzerland, 2018.

[42] *Specification for Additive Manufacturing File Format (AMF)*, document ISO/ASTM 52915:2016, Version 1.2, International Organization for Standardization, Geneva, Switzerland, 2016.

[43] *Standard Terminology for Additive Manufacturing—Coordinate Systems and Test Methodologies*, document ISO/ASTM 52921:2013, International Organization for Standardization, Geneva, Switzerland, 2013.

[44] *Plastics—Determination of Tensile Properties—Part 1: General Principles*, document ISO 527-1:2019, International Organization for Standardization, Geneva, Switzerland, 2019.

[45] *Plastics—Determination of Tensile Properties—Part 2: Test Conditions for Moulding and Extrusion Plastics*, document ISO 527-2:2012, International Organization for Standardization, Geneva, Switzerland, 2012.

[46] *Plastics—Determination of Tensile Properties—Part 3: Test Conditions for Films and Sheets*, document ISO 527-3:2018, International Organization for Standardization, Geneva, Switzerland, 2018.

[47] *Plastics—Determination of Tensile Properties—Part 4: Test Conditions for Isotropic and Orthotropic Fibre-Reinforced Plastic Composites*, document ISO 527-4:1997, International Organization for Standardization, Geneva, Switzerland, 1997.

[48] *Plastics. Determination of Tensile Properties—Part 5: Test Conditions for Unidirectional Fibre-Reinforced Plastic Composites*, document ISO 527-5:2009, International Organization for Standardization, Geneva, Switzerland, 2009.

[49] *Plastics—Determination of Compressive Properties*, document ISO 604:2002, International Organization for Standarization, Geneva, Switzerland, 2002.

[50] *Standard Test Method for Tensile Properties of Plastics*, Standard ASTM D638-14, ASTM International, West Conshohocken, PA, USA, 2014.

[51] *Standard Test Method for Compressive Properties of Rigid Plastics*, Standard ASTM D695-15, ASTM International, West Conshohocken, PA, USA, 2015.

[52] S. Brischetto, C. Ferro, P. Maggiore, and R. Torre, "Compression tests of ABS specimens for UAV components produced via the FDM technique," *Technologies*, vol. 5, no. 2, p. 20, May 2017, doi: 10.3390/technologies5020020.

[53] B. Banjanin, G. Vladic, M. Pál, S. Balos, M. Dramicanin, M. Rackov, and I. Knezevic, "Consistency analysis of mechanical properties of elements produced by FDM additive manufacturing technology," *Matéria (Rio de Janeiro)*, vol. 23, no. 4, Dec. 2018, doi: 10.1590/s1517-707620180004.0584. AQ:7

[54] *Fibre-Reinforced Plastic Composites—Determination of Compressive Properties in the in-Plane Direction*, document ISO 14126:1999, International Organization for Standardization, Geneva, Switzerland, 1999.

[55] *Standard Test Method for Compressive Properties of Polymer Matrix Composite Materials with Unsupported Gage Section by Shear Loading*, Standard ASTM D3410/D3410M-03, ASTM International, West Conshohocken, PA, USA, 2003.

[56] *Fibre-Reinforced Plastic Composites—Determination of the in-Plane Shear Stress/Shear Strain Response, Including the in-Plane Shear Modulus and Strength, by the Plus or Minus 45 Degree Tension Test Method*, document ISO 14129:1997, International Organization for Standardization, Geneva, Switzerland, 1997.

[57] G. Ćwikła, C. Grabowik, K. Kalinowski, I. Paprocka, and P. Ociepka, "The influence of printing parameters on selected mechanical properties of FDM/FFF 3D-printed parts," *IOP Conf. Ser. Mater. Sci. Eng.*, vol. 227, Aug. 2017, Art. no. 012033, doi: 10.1088/1757-899X/227/1/012033.

[58] J. R. C. Dizon, A. H. Espera, Q. Chen, and R. C. Advincula, "Mechanical characterization of 3D-printed polymers," *Additive Manuf.*, vol. 20, pp. 44–67, Mar. 2018, doi: 10.1016/j.addma.2017.12.002.

[59] D. Popescu, A. Zapciu, C. Amza, F. Baciu, and R. Marinescu, "FDM process parameters influence over the mechanical properties of polymer specimens: A review," *Polym. Test.*, vol. 69, pp. 157–166, Aug. 2018, doi: 10.1016/j.polymertesting.2018.05.020.

[60] T. Webbe Kerekes, H. Lim, W. Y. Joe, and G. J. Yun, "Characterization of process—Deformation/damage property relationship of fused deposition modeling (FDM) 3D-printed specimens," *Additive Manuf.*, vol. 25, pp. 532–544, Jan. 2019, doi: 10.1016/j.addma.2018.11.008.

[61] R. J. Zaldivar, D. B. Witkin, T. McLouth, D. N. Patel, K. Schmitt, and J. P. Nokes, "Influence of processing and orientation print effects on the mechanical and thermal behavior of 3D-printed ULTEM 9085 material," *Additive Manuf.*, vol. 13, pp. 71–80, Jan. 2017, doi: 10.1016/j.addma.2016.11.007.

[62] V. Kuznetsov, A. Solonin, O. Urzhumtsev, R. Schilling, and A. Tavitov, "Strength of PLA components fabricated with fused deposition technology using a desktop 3D printer as a function of geometrical parameters of the process," *Polymers*, vol. 10, no. 3, p. 313, Mar. 2018, doi: 10.3390/polym10030313.

[63] Y. Aw, C. Yeoh, M. Idris, P. Teh, K. Hamzah, and S. Sazali, "Effect of printing parameters on tensile, dynamic mechanical, and thermoelectric properties of FDM 3D printed CABS/ZnO composites," *Materials*, vol. 11, no. 4, p. 466, Mar. 2018, doi: 10.3390/ma11040466.

[64] Z. Liu, Q. Lei, and S. Xing, "Mechanical characteristics of wood, ceramic, metal and carbon fiber-based PLA composites fabricated by FDM," *J. Mater. Res. Technol.*, vol. 8, no. 5, pp. 3741–3751, Sep. 2019, doi: 10.1016/j.jmrt.2019.06.034.

[65] S. R. Rajpurohit and H. K. Dave, "Analysis of tensile strength of a fused filament fabricated PLA part using an open-source 3D printer," *Int. J. Adv. Manuf. Technol.*, vol. 101, nos. 5–8, pp. 1525–1536, Apr. 2019, doi: 10.1007/s00170-018-3047-x.

[66] C. Casavola, A. Cazzato, V. Moramarco, and C. Pappalettere, "Orthotropic mechanical properties of fused deposition modelling parts described by classical laminate theory," *Mater. Des.*, vol. 90, pp. 453–458, Jan. 2016, doi: 10.1016/j.matdes.2015.11.009.

[67] A. Alafaghani, A. Qattawi, B. Alrawi, and A. Guzman, "Experimental optimization of fused deposition modelling processing parameters: A design-for-manufacturing approach," *Procedia Manuf.*, vol. 10, pp. 791–803, Jan. 2017, doi: 10.1016/j.promfg.2017.07.079.

[68] R. T. L. Ferreira, I. C. Amatte, T. A. Dutra, and D. Bürger, "Experimental characterization and micrography of 3D printed PLA and PLA reinforced with short carbon fibers," *Compos. B, Eng.*, vol. 124, pp. 88–100, Sep. 2017, doi: 10.1016/j.compositesb.2017.05.013.

[69] B. Akhoundi and A. H. Behravesh, "Effect of filling pattern on the tensile and flexural mechanical properties of FDM 3D printed products," *Experim. Mech.*, vol. 59, no. 6, pp. 883–897, Jul. 2019, doi: 10.1007/s11340-018-00467-y.

[70] D. Croccolo, M. De Agostinis, and G. Olmi, "Experimental characterization and analytical modelling of the mechanical behaviour of fused deposition processed parts made of ABS-M30," *Comput. Mater. Sci.*, vol. 79, pp. 506–518, Nov. 2013, doi: 10.1016/j.commatsci.2013.06.041.

[71] A. R. T. Perez, D. A. Roberson, and R. B. Wicker, "Fracture surface analysis of 3D-printed tensile specimens of novel ABS-based materials," *J. Failure Anal. Prevention*, vol. 14, no. 3, pp. 343–353, Jun. 2014, doi: 10.1007/s11668-014-9803-9.

[72] B. M. Tymrak, M. Kreiger, and J. M. Pearce, "Mechanical properties of components fabricated with open-source 3-D printers under realistic environmental conditions," *Mater. Des.*, vol. 58, pp. 242–246, Jun. 2014, doi: 10.1016/j.matdes.2014.02.038.

[73] B. Rankouhi, S. Javadpour, F. Delfanian, and T. Letcher, "Failure analysis and mechanical characterization of 3D printed ABS with respect to layer thickness and orientation," *J. Failure Anal. Prevention*, vol. 16, no. 3, pp. 467–481, Jun. 2016, doi: 10.1007/s11668-016-0113-2.

[74] J. C. Riddick, M. A. Haile, R. V. Wahlde, D. P. Cole, O. Bamiduro, and T. E. Johnson, "Fractographic analysis of tensile failure of acrylonitrile-butadiene-styrene fabricated by fused deposition modeling," *Additive Manuf.*, vol. 11, pp. 49–59, Jul. 2016, doi: 10.1016/j.addma.2016.03.007.

[75] Z. Weng, J. Wang, T. Senthil, and L. Wu, "Mechanical and thermal properties of ABS/montmorillonite nanocomposites for fused deposition modeling 3D printing," *Mater. Des.*, vol. 102, pp. 276–283, Jul. 2016, doi: 10.1016/j.matdes.2016.04.045.

[76] J. M. Chacón, M. A. Caminero, E. García-Plaza, and P. J. Núñez, "Additive manufacturing of PLA structures using fused deposition modelling: Effect of process parameters on mechanical properties and their optimal selection," *Mater. Design*, vol. 124, pp. 143–157, Jun. 2017, doi: 10.1016/j.matdes.2017.03.065.

[77] N. G. Tanikella, B. Wittbrodt, and J. M. Pearce, "Tensile strength of commercial polymer materials for fused filament fabrication 3D printing," *Additive Manuf.*, vol. 15, pp. 40–47, May 2017, doi: 10.1016/j.addma.2017.03.005.

AQ:8 [78] *Technical Safety Datasheets*, BCN3d Technol., BCN3D Web Site.

[79] *Our Materials*, Stratasys Web Site.

[80] *Materials*, Ultimaker Web Site.

[81] *Material Data*, Ultrafuse Filament Web Site, BASF Forward AM.

[82] A. García-Domínguez, "Methodology for the optimization of parts obtained by additive manufacturing into mass customization strategies," UNED, Tech. Rep., 2019. AQ:9

[83] W. Chen, X. Zheng, and S. Liu, "Finite-element-mesh based method for modeling and optimization of lattice structures for additive manufacturing," *Materials*, vol. 11, no. 11, p. 2073, Oct. 2018, doi: 10.3390/ma11112073.

[84] A. Y. Hussein, "The development of lightweight cellular structures for metal additive manufacturing," vol. 228, 2013. AQ:10

[85] D. Mahmoud and M. Elbestawi, "Lattice structures and functionally graded materials applications in additive manufacturing of orthopedic implants: A review," *J. Manuf. Mater. Process.*, vol. 1, no. 2, p. 13, Oct. 2017, doi: 10.3390/jmmp1020013.

[86] G. Maliaris and E. Sarafis, "Mechanical behavior of 3D printed stochastic lattice structures," *Solid State Phenomena*, vol. 258, pp. 225–228, Dec. 2016, doi: 10.4028/www.scientific.net/SSP.258.225.

[87] B. N. Panda, "Design and development of cellular structure for additive manufacturing," vol. 612, p. 83, 2015. AQ:11

[88] R. Vannutelli, "Mechanical behavior of 3D printed lattice-structured materials," pp. 1–112, Dec. 2017. AQ:12

[89] O. Weeger, N. Boddeti, S. Yeung, S. Kaijima, and M. L. Dunn, "Digital design and nonlinear simulation for additive manufacturing of soft lattice structures," *Additive Manuf.*, vol. 25, pp. 39–49, Jan. 2019.

[90] *Standard Specification for Additive Manufacturing Titanium-6 Aluminum-4 Vanadium With Powder Bed Fusion*, Standard ASTM F2924-14, ASTM International, West Conshohocken, PA, USA, 2014.

[91] *Standard Specification for Additive Manufacturing Titanium-6 Aluminum-4 Vanadium ELI (Extra Low Interstitial) with Powder Bed Fusion*, ASTM International, Standard ASTM F3001-14, West Conshohocken, PA, USA, 2014.

[92] *Standard Specification for Additive Manufacturing Stainless Steel Alloy (UNS S31603) With Powder Bed Fusion*, ASTM International, Standard ASTM F3184-16, West Conshohocken, PA, USA, 2016.

[93] *Mechanical Testing of Metals—Ductility Testing—Compression Test for Porous and Cellular Metals*, document ISO 13314:2011, International Organization for Standardization, Geneva, Switzerland, 2011.

[94] *Standard Test Methods of Compression Testing of Metallic Materials at Room Temperature*, Standard ASTM E9-19, ASTM International, West Conshohocken, PA, USA, 2019.

[95] *Standard Test Method for Flatwise Tensile Strength of Sandwich Constructions*, Standard ASTM C297/C297M-16, ASTM International, West Conshohocken, PA, USA, 2016.

[96] *Standard Test Method for Node Tensile Strength of Honeycomb Core Materials*, Standard ASTM C363/C363M-16, ASTM International, West Conshohocken, PA, USA, 2016.

[97] *Standard Test Method for Edgewise Compressive Strength of Sandwich Constructions*, Standard ASTM C364/C364M-16, ASTM International, West Conshohocken, PA, USA, 2016.

[98] *Standard Test Method for Shear Properties of Sandwich Core Materials*, Standard ASTM C273/C273M-20, ASTM International, West Conshohocken, PA, USA, 2020.

[99] *Standard Test Method for Core Shear Properties of Sandwich Constructions by Beam Flexure*, Standard ASTM C393/C393M-16, ASTM International, West Conshohocken, PA, USA, 2016.

[100] *Standard Terminology for Additive Manufacturing-Coordinate Systems and Test Methodologies (Withdrawn 2013)*, Standard ASTM F2921-11e3, ASTM International, West Conshohocken, PA, USA, 2011.

[101] *Standard Practice for Reporting Data for Test Specimens Prepared by Additive Manufacturing*, Standard ASTM F2971-13, ASTM International, West Conshohocken, PA, USA, 2013.

[102] *Standard Specification for Additive Manufacturing Nickel Alloy (UNS N07718) With Powder Bed Fusion*, Standard ASTM F3055-14a, ASTM International, West Conshohocken, PA, USA, 2014.

[103] *Standard Specification for Additive Manufacturing Nickel Alloy (UNS N06625) With Powder Bed Fusion*, Standard NoASTM F3056-14e1, ASTM International, West Conshohocken, PA, USA, 2014.

[104] *Standard Specification for Powder Bed Fusion of Plastic Materials*, Standard ASTM F3091/F3091M-14, ASTM International, West Conshohocken, PA, USA, 2014.

[105] *Standard Guide for Evaluating Mechanical Properties of Metal Materials Made Via Additive Manufacturing Processes*, Standard ASTM F3122-14, ASTM International, West Conshohocken, PA, USA, 2014.

[106] *Standard Guide for Directed Energy Deposition of Metals*, Standard ASTM F3187-16, ASTM International, West Conshohocken, PA, USA, 2016.

[107] *Standard for Additive Manufacturing—Finished Part Properties—Standard Specification for Cobalt-28 Chromium-6 Molybdenum Via Powder Bed Fusion*, Standard ASTM F3213-17, ASTM International, West Conshohocken, PA, USA, 2017.

[108] *Standard for Additive Manufacturing—Post Processing Methods—Standard Specification for Thermal Post-Processing Metal Parts Made Via Powder Bed Fusion1, 2*, Standard ASTM F3301-18a, ASTM International, West Conshohocken, PA, USA, 2018.

[109] *Standard for Additive Manufacturing—Finished Part Properties—Standard Specification for Titanium Alloys via Powder Bed Fusion*, Standard ASTM F3302-18, ASTM International, West Conshohocken, PA, USA, 2018.

[110] *Standard for Additive Manufacturing—Process Characteristics and Performance: Practice for Metal Powder Bed Fusion Process to Meet Critical Applications*, Standard ASTM F3303-18, ASTM International, West Conshohocken, PA, USA, 2018.

[111] *Standard for Additive Manufacturing—Finished Part Properties—Specification for AlSi10Mg With Powder Bed Fusion—Laser Beam*, Standard ASTM F3318-18, ASTM International, West Conshohocken, PA, USA, 2018.

[112] *Standard Guide for Assessing the Removal of Additive Manufacturing Residues in Medical Devices Fabricated by Powder Bed Fusion*, Standard ASTM F3335-20, ASTM International, West Conshohocken, PA, USA, 2020.

[113] *Additive Manufacturing—Test Artifacts—Geometric Capability Assessment of Additive Manufacturing Systems*, document ISO/ASTM 52902:2019, Geneva, Switzerland, 2019.

[114] *Additive Manufacturing—Material Extrusion-Based Additive Manufacturing of Plastic Materials—Part 1: Feedstock Materials*, document ISO/ASTM 52903-20, ISO/ASTM International, Geneva, Switzerland, 2020.

[115] *Additive Manufacturing—Process Characteristics and Performance—Practice for Metal Powder Bed Fusion Process to Meet Critical Applications*, document ISO/ASTM 52904:2019, ISO/ASTM International, Geneva, Switzerland, 2019.

[116] *Additive Manufacturing—Feedstock Materials—Methods to Characterize Metal Powders*, document ISO/ASTM 52907:2019, ISO/ASTM International, Geneva, Switzerland, 2019.

[117] *Additive Manufacturing—Design—Part 1: Laser-Based Powder Bed Fusion of Metals*, ISO/ASTM 52911-1:2019, ISO/ASTM International, Geneva, Switzerland, 2019.

[118] *Additive Manufacturing—Design—Part 2: Laser-Based Powder Bed Fusion of Polymers*, document ISO/ASTM 52911-2:2019, ISO/ASTM International, Geneva, Switzerland, 2019.

[119] *Standard Guide for Characterizing Properties of Metal Powders Used for Additive Manufacturing Processes*, Standard ASTM F3049-14, ASTM International, West Conshohocken, PA, USA, 2014.

[120] *Guide for Additive Manufacturing—Design—Directed Energy Deposition*, document ISO/ASTM 52922-19, ISO/ASTM International, Geneva, Switzerland, 2019.

[121] *Standard Terminology for Additive Manufacturing Technologies (Withdrawn 2015)*, Standard ASTM F2792-12a, ASTM International, West Conshohocken, PA, USA, 2009.

[122] *Standard Specification for Additive Manufacturing File Format (AMF) Version 1.1 (Withdrawn 2013)*, Standard ASTM F2915-12, ASTM International, West Conshohocken, PA, USA, 2012.

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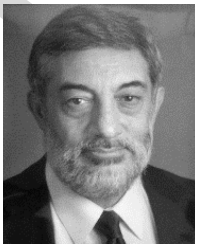

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