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Review of surface metrology artifacts for polymer-based additive manufacturing

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Abstract

Test artifacts, resembling real machine parts, allow quantitative evaluation of system performance and insight into individual errors, aiding in improvement and standardization in additive manufacturing. The article provides a comprehensive overview of existing test artifacts, categorized based on geometric features and material used. Various measurement techniques such as stylus profilometry and computed tomography are employed to assess these artifacts. Specific artifact categories include slits, angular or linear features, variable surfaces, and others, each accompanied by examples from research literature, highlighting diverse artifact designs and their intended applications. The paper underscores the importance of user-friendly and unambiguous artifacts for dimensional control, particularly in surface metrology. It anticipates the continued growth of metrological verification in future manufacturing environments, emphasizing the need for precise and reliable measurement results to support decision-making in production conditions.

1. Introduction

Additive Manufacturing (AM), commonly known as 3D printing, is a process of fabricating objects by layering processed material based on three-dimensional model data [1]. The core of additive manufacturing technologies lies in the successive construction of elements layer by layer, contrasting with subtractive methods where the element is produced through subtractive operations [2]. Multiple AM technologies exist, such as stereolithography [3], laser sintering [4], and multi-jet printing [5], all covered in the international ASTM standard [6].

With the continuous evolution of additive methods, there is a growing need for a deeper understanding of the technology itself by characterizing the quality of the process and, in turn, produced parts. Two approaches to assessing these methods have been defined. The first involves a series of in-situ measurements of components being produced or process characteristics during the fabrication [7]. This method necessitates the placement of additional sensors in the machine workspace, capturing relative positions, orientations, velocities, accelerations or other characteristics of the fabrication process. In the case of AM systems, this approach is often challenging or impossible due to moving elements that are inaccessible to measuring equipment, posing potential hazards associated with the applied manufacturing technology, such as high-power lasers. The second approach considers measurements of a produced test artifact made in a specific manufacturing system [8].

Evaluating the performance of manufacturing process by using a real produced test artifact allows an insight into the effect of individual errors in the system which finally contribute to errors in the entire part. The primary advantage of test artifacts is their production, with elements aligning with the real purpose of the system and usually not requiring specialized measuring equipment

[9]. In most cases, conventional measuring equipment suffices. The primary goal of a test artifact is to determine the quantitative performance of the system. The advantage of a standardized artifact is its reproducibility in different systems, allowing for relatively easy comparison [10]. With proper and deliberate design, a test artifact can highlight the limitations of the machine itself, becoming a verification method between system users and manufacturers. This facilitates improvements and, consequently, the continuous development of AM methods.

This article provides an overview of existing test artifacts used to characterize AM systems. Additionally, a strategy for standardizing test artifacts to characterize the performance of AM systems is discussed. These principles are supported by existing and published data from the literature, aiming to systematize and compile current achievements related to the verification of additive systems, ultimately allowing for their further development.

2. Methods

An important aspect determining the execution of a literature review is the selection and screening of appropriate scholarly sources. Significant topics and key issues, which are the subject of the review below, have been identified. A systematic analysis of available literature has been conducted, considering both the oldest and the most recent publications. In this way, a comprehensive compilation of test artifacts used in additive manufacturing utilizing polymers has been accomplished. In this aspect, the approach was guided by:

- 0ontent analysis:

Each article was critically assessed in terms of its scientific and methodological value. The unit of analysis was defined, referring to the entirety of the publication rather than just its fragments. This allowed for a comprehensive and holistic approach capturing the full research aspect. Categories referring solely to 3D printing based solely on polymer manufacturing were identified as the criterion for content categorization. Content analysis employed the triangulation method, verifying proposed methods by authors with other sources confirming their validity. In this way, contents most aligned with defined assumptions were selected.

- Research approach:

The methodology used by the authors was taken into account. Understanding its utility and validity in the context of test artifacts was crucial. During selection, authors' utilization of verification and control methods for used geometries in creating test artifacts was key. Proposals that did not consider measurement methods were rejected and not considered during the analysis. This eliminated purely theoretical considerations not verified or tangibly tested through production practice. Additionally, it was checked whether authors referred to applicable standards, analyzing their content as references to proposed geometries. Attention was paid to authors' research objectives and assessed whether they aligned with the review's own objectives. Means of analysis and interpretation of authors' research, including statistical analysis and case studies, were considered. It was important for authors not to focus solely on one investigated geometry, but on the diversity of produced and proposed geometric features. This allowed for an assessment of the reliability and validity of observations.

- Authors' research perspective:

The theoretical frameworks used in proposed theories and scientific paradigms by authors were considered. The experience and research areas of scientists proposing test artifact solutions were taken into account. This allowed for the utilization of the diversity of interests and approaches to scientific aspects. Authors' methodological approach and their choice of analysis were important. Attention was paid to whether authors represented quantitative and qualitative approaches and whether they addressed issues related to self-criticism and aspects requiring improvement. This was related to the impact on the scope of research and the way results were interpreted, which had a direct impact on the approach to the problem at hand. Additionally, it was considered whether authors included practical implications in formulating recommendations for technical manufacturing practice. These aspects allowed for the assessment of the validity and credibility of results on independent issues related to proposed test artifact geometries.

Reports on the updates of test artifacts and new solutions systematically appear in the literature. New trends and directions of development are also highlighted. The first publication of this kind emerged in 2012. Moylan et al. [11] identified the fundamental geometries used in test artifacts, providing several examples of their implementation in test standards by other authors. In 2014, Bauza et al. [12] emphasized the use of lattice structures in test artifacts. In 2016, Thompson et al. [13] summarized the utilization of test artifacts in tomographic analysis of material defects. A year later, Rebaioli et al. [14] compiled and categorized test standards considering material and technology types without incorporating measurement geometry. In 2018, Shah et al. [15] quantitatively examined the nature of the influence

of computed tomography results on previously used standards. In the same year, Toguem et al. [16] extracted specific features from existing test artifacts and their impact on GD&T characteristics. Additionally, during the same period, Townsend et al. [17] compiled publications related to test artifacts in terms of surface analysis. Singh et al. [18] addressed the use of specific features performed on test artifacts in the context of GD&T. Two years later, Pastre et al. [19] focused on compiling the methodologies used in designing test artifacts. In 2020, Minetola et al. [20] investigated the issues of used test artifacts in comparison to the quantitative obtained tolerances. In the same year, Gallant et al. [21] conducted a qualitative comparison of artifacts used in the production of stainless steel components. Vincente et al. [22] compiled artifacts used directly for metrological research purposes. In 2020, Vorkapic et al. [23] listed the main utilized artifacts and indicated possibilities for improving the described test standards. In 2021, Budzik et al. [24] identified standards used in test artifacts for 3D printing and highlighted the methodology for verifying the quality of emerging test standards. In the same year, Spitaels et al. [25], using their literature review, proposed changes in manufactured artifacts. Conversely, in 2022, Kawalkar et al. [26] compiled all standards and associated guidelines considering the conditions for producing test artifacts. Additionally, they highlighted key and critical geometries in specific standards.

Taking the above into account, it should be noted that none of the aforementioned authors conducted a literature review strictly and comprehensively addressing issues related to the use of polymeric materials in manufacturing test artifacts. They did not specify this in their research. Considering the constantly evolving nature of 3D printing, issues related to artifacts made from polymers should be considered separately from those made from metal alloys. This is due to the different essence and technology of producing the geometries of manufactured elements. Additionally, it should be noted that the latest publication containing and summarizing the use of test standards was conducted in 2022. With continuously evolving additive techniques, ongoing verification of proposed solutions is necessary. Therefore, in the following section, a compilation of the latest solutions is proposed, taking into account innovations and revisions of test standards resulting from previous findings. It was necessary to refresh the compilation and showcase the latest trends in test standard design.

3. Overview of technologies, materials and features

Additive manufacturing gained its significance in the late 1980s. Stereolithography (SLA) was the first commercially successful technology, followed closely by Fused Deposition Modeling (FDM), Laminated Object Manufacturing (LOM), and Selective Laser Sintering (SLS). As AM advanced, numerous other technologies, such as material spraying, were introduced to the market. The development of stereolithography was linked to the recognition of the standardization of accuracy tests [27]. Consequently, it was acknowledged that a standard test artifact should:

- be large enough to test the manufacturing performance near the printing platform edges,
- include a significant number of small, medium, and large objects with both holes and protruding features,
- have a reasonable creation time for the artifact,
- not consume a large amount of material,
- be „easily" measurable,
- contain geometric features which resemble the real machine parts (e.g.: thin walls, flat surfaces, holes, etc.).

Other researchers strictly adhered to these criteria [28]. Bauza et al. referred to these principles but added that artifacts should contain features along all axes and should include features to determine the minimum achievable size of an element [12]. While many of these features are indeed important for designing a test artifact, it should be noted that an ideal artifact should not only reveal most errors and limitations of the system but also correlate them.

Kruth et al. [29] observed that a test artifact should not only assess system limitations but should also contain information on how to improve the manufacturing process by tuning the technological parameters. Furthermore, Scaravetti et al. stated that artifact verification should not only allow the identification and quantitative determination of defects but primarily determine their sources [30]. Therefore, it was established that a test artifact should additionally:

- have simple geometric shapes enabling clear determination and easy control of geometry,
- not require additional post-processing,
- allow measurements and repeatability analysis.

Moreover, several researchers emphasized the need for the test artifact to include multiples of the same shape to enable measurement repeatability. However, incorporating multiples of the same shape only tests the ability to create the same shape in different locations of the pattern [31]. As different conditions may result

in various systematic errors in machine workspace, this leads to differences in the produced shapes in different locations. Therefore, if the system produces multiple artifacts with a high level of repeatability, the shapes created in the same location in the machine workspace would be exactly the same but in a distorted form.

Although many test artifacts for AM have been proposed in the literature (discussed later in the paper), not all authors adhere to the discussed guidelines, and none of them has undergone a formal standardization procedure. In this paper, we systematize different approaches and highlight differences in geometric features authors focused on in their developed artifacts.

Table 1 presents the overview of artifact geometries depending on the manufacturing technology. According to the analyzed literature, the most commonly used printing technology, as indicated by the authors was Selective Laser Sintering (SLS) – 23 times, next Stereolithography (SLA) – 19 times and Fused Deposition Modeling (FDM) – 11 times. The most frequently chosen geometries for SLS were angular surfaces (22 %), followed by cuboid at 17 %, cylindrical, holes, cracks, spheres each at 13 %, cones at 9 %.

Table 2 illustrates the distribution of the chosen occurrence of artifact geometries based on the printing material according to the analyzed literature. Nylon was the most frequently chosen (19 times), followed by ABS/PLA alloys (15 times). The most commonly chosen geometry for nylon was angular surfaces and cuboid – each 22 %, cylindrical artifacts and spheres at each 17 %, holes and cones at each 13 %, slits at 6 %.

Table 3 presents the distribution of the occurrence of measurement techniques in specific literature positions. The authors chose various measurement techniques 17 times in total. CMM was selected 6 times (37 %); contact profilometer 5 times (28 %); 3D scanners 3 times (18 %); optical profilometry 2 times (11 %); computer tomography 1 time (6 %).

Table 1. Occurrence of types of artifacts in the literature depending on 3D printing technology

Features / Technology	Cylinder	Holes	Angular surfaces	Cracks	Cone	Cuboid	Sphere
FDM	Kruth [33] Grimm et al. [38]	Kruth [33] Ippolito et al. [34]	Kruth [33] Ippolito et al. [34] Moylan et al. [37] Grimm et al. [38]			Moylan et al. [37] Grimm et al. [38]	Grimm et al. [38]
SLA	Fahad et al. [32] Mahesh et al. [35] Grimm et al. [38]	Fahad et al. [32] Mahesh et al. [35]	Mahesh et al. [35] Moylan et al. [37] Grimm et al. [38]	Mahesh et al. [35] Kim et al. [36]	Fahad et al. [32] Mahesh et al. [35]	Fahad et al. [32] Mahesh et al. [35] Moylan et al. [37] Grimm et al. [38]	Fahad et al. [32] Mahesh et al. [35] Grimm et al. [38]
SLS	Fahad et al. [32] Mahesh et al. [35] Grimm et al. [38]	Fahad et al. [32] Mahesh et al. [35] Kruth et al. [40]	Mahesh et al. [35] Moylan et al. [37] Grimm et al. [38] Jansson et al. [39] Kruth et al. [40]	Mahesh et al. [35] Kim et al. [36] Kruth et al. [40]	Fahad et al. [32] Mahesh et al. [35]	Fahad et al. [32] Mahesh et al. [35] Moylan et al. [37] Grimm et al. [38]	Fahad et al. [32] Mahesh et al. [35] Grimm et al. [38]

Table 2. The occurrence of types of artifacts in the literature depending on the material of manufacture

Features / Material	Cylinder	Holes	Angular surfaces	Slits	Cone	Cuboid	Sphere
Nylon	Fahad et al. [32] Mahesh et al. [35] Grimm et al. [38]	Fahad et al. [32] Mahesh et al. [35]	Mahesh et al. [35] Moylan et al. [37] Grimm et al. [38] Jansson et al. [39]	Mahesh et al. [35]	Fahad et al. [32] Mahesh et al. [35]	Fahad et al. [32] Mahesh et al. [35] Moylan et al. [37] Grimm et al. [38]	Fahad et al. [32] Mahesh et al. [35] Grimm et al. [38]
Acrylate	Kruth [33] Mahesh et al. [35] Grimm et al. [38]	Kruth [33] Mahesh et al. [35]	Kruth [33] Mahesh et al. [35] Moylan et al. [37] Grimm et al. [38]	Mahesh et al. [35]		Moylan et al. [37] Grimm et al. [38]	Grimm et al. [38]
ABS/PLA	Mahesh et al. [35] Grimm et al. [38]	Mahesh et al. [35]	Mahesh et al. [35] Kim et al. [36] Moylan et al. [37] Grimm et al. [38]	Mahesh et al. [35] Kim et al. [36]	Mahesh et al. [35]	Mahesh et al. [35] Moylan et al. [37] Grimm et al. [38]	Mahesh et al. [35] Grimm et al. [38]
Epoxy resin		Ippolito et al. [34]	Ippolito et al. [34]			Ippolito et al. [34]	

Table 3. The occurrence of measurement techniques for measuring elements made with 3D printing

Article \ M. method	Contact profilometer	X-ray computed tomography	CMM	Optical profilometer	3D scanner
Moylan et al. [31]	x		x	x	
Fahad et al. [32]	x		x		
Kruth [33]			x		
Ippolito et al. [34]	x		x		
Mahesh et al. [35]			x		
Kim et al. [36]	x			x	x
Moylan et al. [37]					x
Grimm et al. [38]			x		x
Jansson et al. [39]		x			
Kruth et al. [40]	x				

4. Artifact geometries

4.1. Slits

The first category of designed artifacts encompasses standards incorporating slit features [35]. Kim et al. devised patterns that take into account two aspects of slits [36]. The first one involves the creation of vertical plates arranged in two rows on a stable base. The plates in the first row are shorter than those in the second row, maintaining a consistent length for all geometric features. Each pair of plates exhibits a designated difference in thickness (see Fig. 1). The second aspect entails the design of a cuboid with perpendicular slots spanning its entire thickness and varying in widths. The height of the slots remains constant (see Fig. 1).

4.2. Angular artifacts

Kim et al. conducted research on a compact angular test artifacts [36]. They proposed creating nine rectangular planes, each made at a different incline angle to the printer table within the range of 10° to 90° (with a 10° iteration) (Fig. 6).

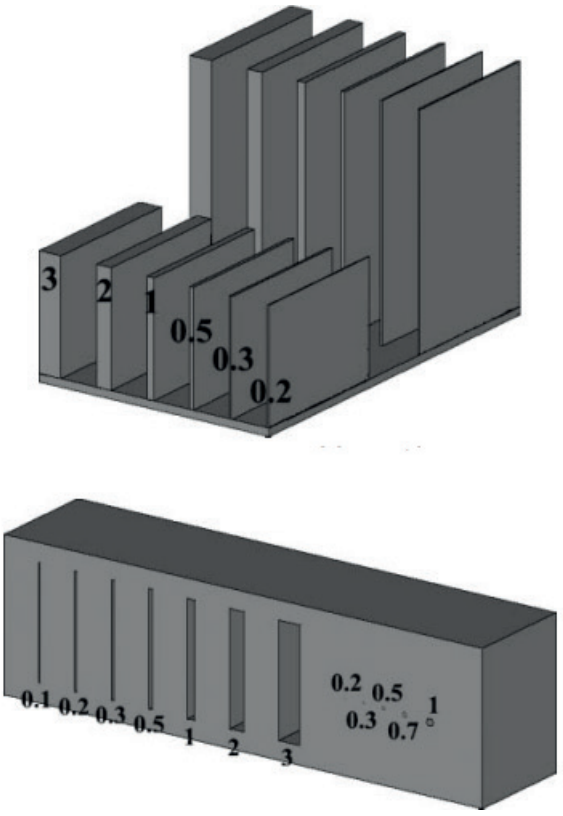


Fig. 1. Example of a chink standard [36]

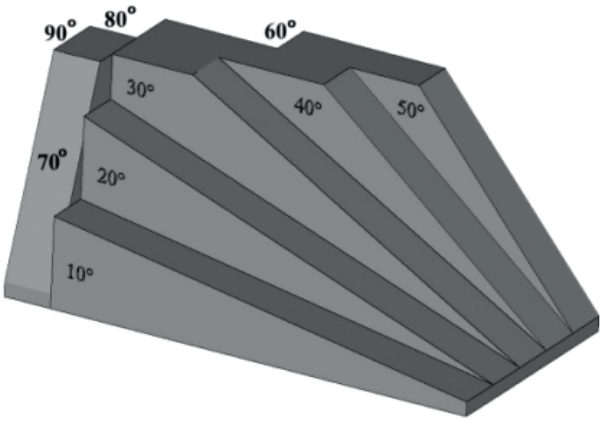


Fig. 2. Test artifacts of planes made at an angle to the plane of the printer table [36]

Moylan, following ASTM F42/ISO TC 261 standards, proposed creating cuboidal plates mounted at different angles on a cylinder (Fig. 10) [37]. The plates, along with the cylinder, were made monolithically during one printing process.

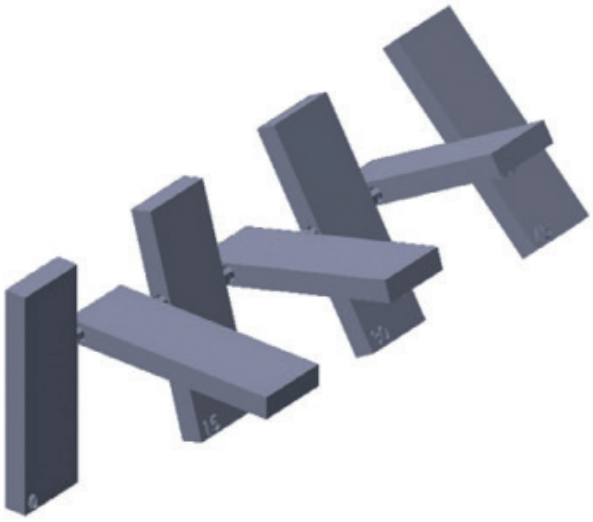


Fig. 3. Angle patterns of tiles suspended on a cylinder [37]

Grimm et al. designed a pattern based on the geometry of a sphere [38]. Cuboidal structures with a square base were created on its surface. This resulted in the printing of cuboids at various angles depending on their position relative to the center of the sphere (Fig. 8). The entire structure is monolithic.

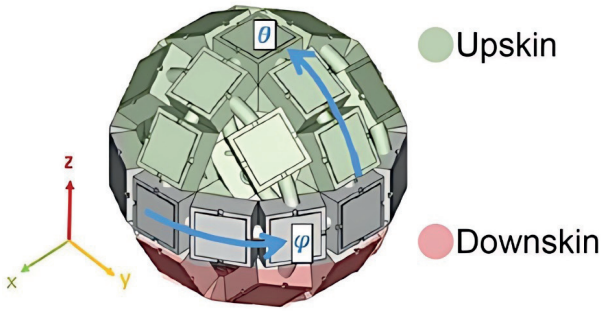


Fig. 4. A reference sphere with cuboids marked on its surface [38]

Jansson and Pejryd studied the influence of the orientation of printed tensile bars on mechanical strength relative to the printer table and at different angular positions concerning the reference point – the starting position of printing (Fig. 9) [39].

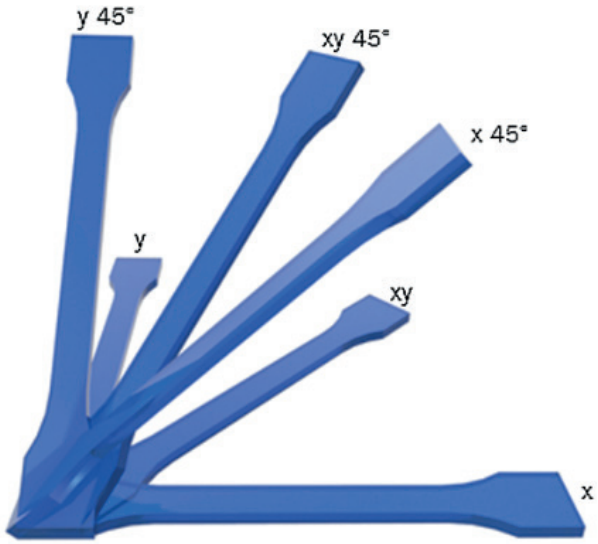


Fig. 5. Angular positioning of samples for testing the influence of printing direction on fatigue strength [39]

4.3. Multiple feature artifacts

Fahad and Hopkinson designed a pattern based on solids: cylinders, cones, cubes, hemispheres, and triangular-based prisms [32]. The solids were produced on different sides in different positions on the base plate. In some geometries, through-holes with a circular cross-section were implemented (Fig. 25).

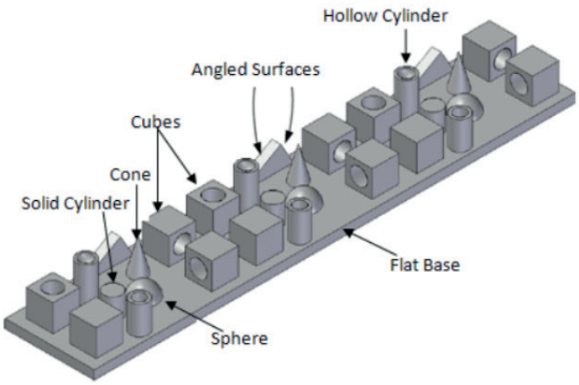
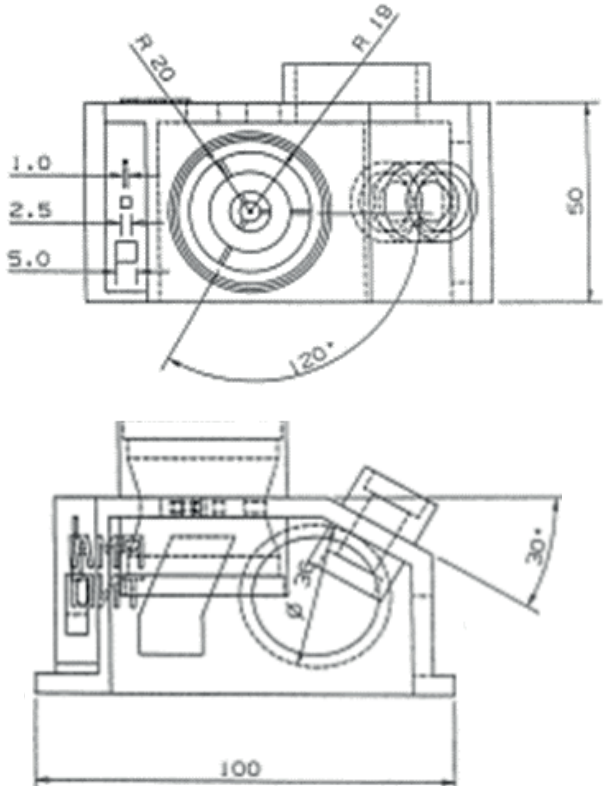


Fig. 6. Test standard by M. Fahad and N. Hopkinson [32]



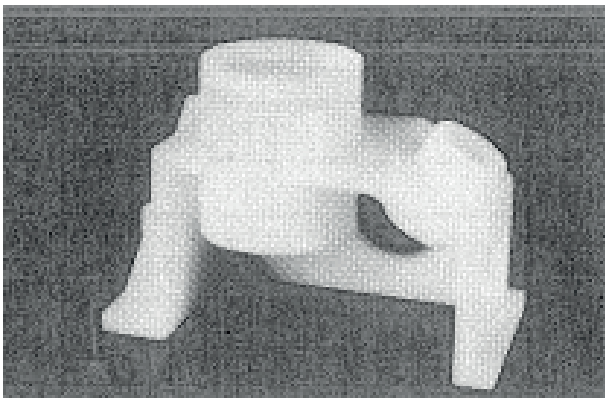


Fig. 7. Kruth's test artifact [33]

J. Kruth, one of the pioneers of additive technologies over 40 years ago, drew attention to the emerging problem of verifying quality and studying the influences of executed geometries on the quality of the product [33]. He initiated the creation and design of test artifacts, proposing an artifact containing multiple geometries based on the most commonly manufactured shapes. This included internal holes of varying diameters, distances between individual surfaces, and slots of different sizes (Fig. 23.).

Ippolito et al. study mention Gargiulo's artifact [34]. It consists of the construction of four interconnected rectangular prisms with square-section holes connected by six plates. Each plate and rectangular prism has a defined, specific geometry and dimensions subject to verification (Fig. 24).

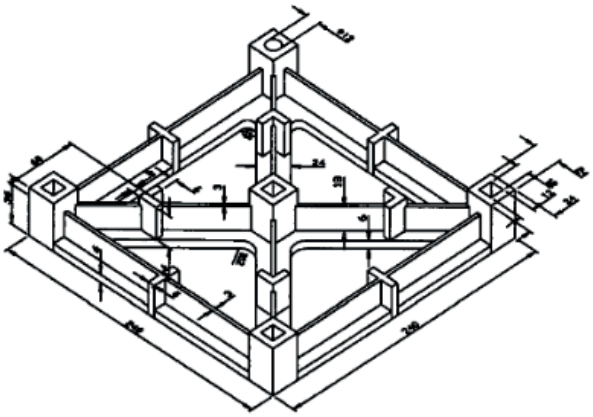


Fig. 8. Gargiulo's artifact [34]

Mahesh et al. [35] proposed a similar pattern concept to the work by Moylan et al. [31]. The artifacts were all placed on a square plate, featuring inclined surfaces, stepped constructions, or holes with different cross-sections. Slots were also implemented on the lateral surfaces of the base plate (Fig. 27).

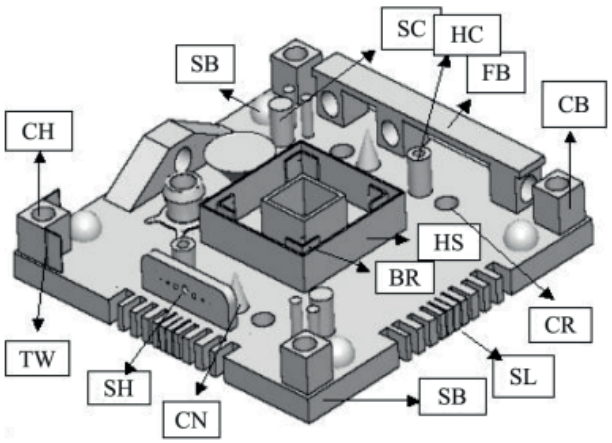


Fig. 9. Artifacts with various geometries in one test pattern according to M. Mahesh et al. [35]

Kruth et al. also proposed a comprehensive test pattern containing various artifact geometries [40]. In addition to creating cylinders and holes (in cross-section and along the length) with different diameters, sharp corners were designed at various angles in the cross-section of the base plate. Additionally, non-through holes with a square cross-section were proposed in very close proximity to each other. This allowed verification of the realization of the thinness of neighboring walls (Fig. 32).

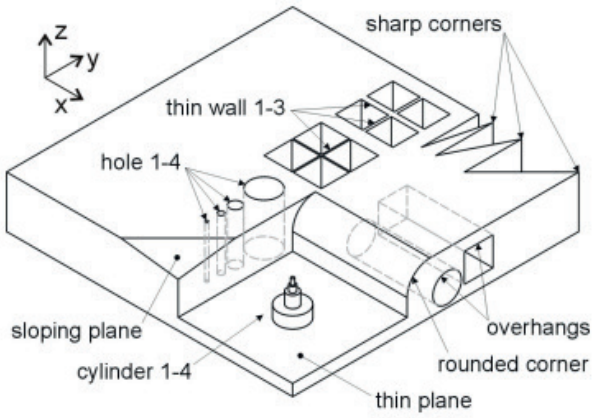


Fig. 10. Comprehensive test pattern with various artifact geometries according to J. P. Kruth et. al. [40]

5. Conclusion

The article discusses the pivotal role of test artifacts in improving production by establishing geometric and dimensional control. It presents the main features of artifacts, encompassing standard objects with simple geometries (cubes, rectangular prisms, etc.) and specific methods for specialized applications. Additionally, the article provides guidelines regarding the design, purpose, and utilization of individual dimensional artifacts. Emphasis is placed on underscoring the impact and significance of test artifacts, which remain fundamental for the verification and calibration of machines and technological processes.

The article notes the importance of these artifacts being user-friendly, suitable for operation in challenging conditions, and unambiguous in interpreting results. In the field of surface metrology, there is a need to develop methods and artifacts for determining the fidelity of topography, especially in additive manufacturing processes involving complex surfaces and angles. Parts produced using additive manufacturing methods with hidden or internal features pose contemporary measurement challenges, prompting the development of new artifact solutions tailored to specific tasks.

The article also addresses issues related to the materials used in designing and creating test patterns, emphasizing that authors often align the measurement method with the manufacturing material. Such an approach enables the creation of dedicated solutions that meet both technological and verification needs. Similarly, geometric considerations in artifact design are shaped by the material and the printing technology itself. This directly influences the quality of standards and their subsequent usefulness in verification.

The authors anticipate that in future manufacturing environments, the importance of metrological verification and the certainty of measurement results will continue to grow. Advanced technologies based on automation require precise and reliable information about the components being manufactured. Only when significant functional features of components are measured with specified uncertainties can appropriate decisions be made regarding compliance with production conditions.

According to the authors, test standards still have many limitations, stemming from technological issues or the nature of 3D printing itself. Problematic becomes the execution of vertical holes or closed geometries due to the necessity of designing support structures. Additionally, attention must be paid to limitations related to the execution of spherical geometries, where it is crucial to adjust the printing process and head movement

characteristics. Considerations regarding surface design are also important, including determining the observation scale and selecting appropriate verification methods. Currently, this is the biggest limitation associated with the latest trends in surface design for 3D printing. These and other limitations pose challenges that will be addressed in future test patterns. However, it is important to continue meeting the requirements set by industry and academia. Therefore, constant verification and improvement of previously created standards are essential.

The above article is the first to address measurement-material-technology-artifact test issues, comprehensively encompassing all these features. The authors focused solely on one group of 3D printing related to polymer materials. This allowed for a complete literature review considering the historical development of individual standards. Additionally, the latest solutions and trends in test artifact design were showcased. This was necessary as continuously evolving additive technologies entail new user requirements. Another positive aspect of this review is that the last similar article was published in 2022, highlighting the need for a refreshed analysis. With increasing requirements come verification needs and quality criteria. Hence, the authors continually improve previous versions of test standards. This article compiled these solutions, providing a comprehensive overview of test standards produced using additive techniques with polymer materials.

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