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ORIGINAL ARTICLE

A review on benchmark artifacts for evaluating the geometrical performance of additive manufacturing processes

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Abstract In recent years, additive manufacturing (AM) has undergone a rapid growth, therefore several processes based on different working principles (e.g. photopolymerization, sintering, extrusion, material jetting, etc) are now available and allow to manufacture parts using a wide range of materials. Consequently, the so-called benchmark artifacts are necessary to assess the capabilities and limitations of each AM process or to compare the performance of different processes. This paper focuses on the benchmark artifacts for evaluating the geometrical performance of AM processes and proposes an extensive review of the available literature, analyzing the design of such test parts in detail. The investigated test parts are classified according to the process aspect that they are able to evaluate (dimensional/geometrical accuracy, repeatability, minimum feature size) and the combination AM process/materials for which they have been used. In addition, the paper draws a summary of guidelines to design benchmark artifacts for geometrical performance evaluation.

Keywords Additive manufacturing · Rapid prototyping · Performance evaluation · Benchmarking · Test artifact

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1 Introduction

The additive manufacturing (AM) processes are defined as the technologies capable of "joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive or formative manufacturing methodologies" [1].

The first AM technology to be developed was stereolithography, which was commercialized by 3D Systems in 1987. Since then, this field had a rapid growth and nowadays several AM processes based on different working principles (e.g., photopolymerization, sintering, extrusion, and material jetting) are available, allowing to build parts in a wide range of materials (polymers, ceramics, metals, etc.). As the number of processes and technologies increased, it increased as well the need and request for tools and procedures allowing to assess the technological capabilities and limitations of a specific process or even to compare the performances of different processes. Therefore, many authors developed the so-called benchmark artifacts.

A sound classification of benchmark artifacts for AM processes in three groups according to their main purpose was firstly proposed by Mahesh [2].

The first group, "geometrical benchmark," contains the benchmark artifacts that are used to check and compare the geometrical/dimensional performance (i.e., tolerances, accuracy, repeatability, and surface finish) of one or more AM systems. This paper focuses on this group and investigates the design of such test parts, since the results of this kind of performance evaluation are directly exploitable by the users selecting a suitable process/material combination for their specific application.

The benchmark artifacts of the second group allow to characterize the mechanical properties (i.e., tensile/compression strength, shrinkage, warping, and creep characteristics) of parts generated by a certain AM technology. These test parts are usually designed based on standards about mechanical properties testing. Some examples can be found in [3–7]. Such parts can be referred to as “mechanical benchmarks” and are essential when manufacturing structural components.

The third group, “process benchmark,” consists of the benchmark artifacts with the aim of establishing the optimum process parameters (i.e., part orientation, support structures, layer thickness, speed). It is extremely difficult to design a universal test part for process optimization due to the great variety of working principles at the base of AM technologies. However, some studies have used artifacts designed for geometrical benchmarking (Section 4) or mechanical benchmarking ([3, 4]), while other studies based their optimization procedures on elementary test parts (e.g., [8–10]).

This paper presents the result of an extensive review of the available literature, discussing the proposed benchmark artifacts for evaluating the geometrical performance of AM processes (Section 2). Each selected benchmark is reviewed highlighting its main geometrical features and design purpose. Following this detailed analysis, a summary of the main characteristics of these benchmark artifacts is provided in Section 2.1. Finally, Section 3 discusses the guidelines to design benchmark artifacts for geometrical performance evaluation, focusing on overall part dimensions (Section 3.1.1), feature geometry (Section 3.1.2), feature dimensions (Section 3.1.3), and feature position and orientation (Section 3.1.4). Section 3.2 briefly discusses measurement issues to be considered in the design of the benchmark part. Conclusions are then drawn in Section 4.

2 Benchmark artifacts for geometrical performance evaluation

The benchmark artifacts for geometrical performance determination can be specifically designed to evaluate one or more of the following main aspects of AM processes: dimensional or geometrical accuracy, repeatability, and feature minimum size.

Concerning repeatability, Moylan et al. [11, 12] highlight that designing a benchmark artifact with multiple identical features only allows to evaluate the system capability to produce that same feature at different places within the building platform (“spatial repeatability”), but strictly speaking, it does not measure the process repeatability. However, for the sake of simplicity, “repeatability” will be used instead of “spatial repeatability” throughout the paper.

Table 1 summarizes the benchmark artifacts existing in literature and classifies them according to the process aspects that they are able to evaluate and the combination AM process/materials for which they have been tested.

The first benchmark artifact for AM accuracy evaluation was proposed by Kruth [13] in 1992 to assess the overall performance of different AM techniques (SL, SLS, and LOM). This U-shaped part (Fig. 1) contains several geometrical features (e.g., vertical and inclined cylinders, flat and inclined surfaces, squares, pegs, etc.), but none of them is repeated, hence this artifact cannot be used to test the process repeatability

Wohlers [14] described a study performed by Chrysler’s Jeep and Truck Engineering, where a benchmark artifact (i.e., the speedometer adapter shown in Fig. 2) was manufactured using five different technologies (SL, SLS, LOM, SGC, and FDM). The parts were measured just to verify that they were within specifications, but the accuracy of AM processes was not studied in detail.

As reported by Van Putte [15], Eastman Kodak proposed a benchmark artifact (Fig. 3) to compare the capabilities of some AM system based on SL, SLS, LOM, and SGC processes. Both this part and the one by Chrysler’s Jeep and Truck Engineering comprise only a few features that are interesting for the proposing company, therefore their usefulness is limited.

The artifact presented by Lart [16] (Fig. 4) included many small and medium features, since it was designed to test the process ability to produce fine details. The drawback of this part is that many of its features are difficult to access by a typical coordinate measuring machine (CMM).

Childs and Juster [17] designed a totally different benchmark artifact (Fig. 5) containing repeated features to test the process repeatability. In their study, the authors used the proposed part to evaluate both linear accuracy and repeatability of four different AM processes, i.e., SL, SLS, FDM ,and LOM. The artifact features have dimensions of different magnitude order to assess the process accuracy with respect to different scales. However, the freeform features are difficult to measure and the base surface is quite large, thus warping is likely to occur.

The paper written by Aubin [18] presents the results of a worldwide comparison of several commercial AM technologies from the economic and technical point of view. This investigation was performed within the Intelligent Manufacturing Systems (IMS) project. The IMS parts (Fig. 6) were proposed to benchmark the pre-processing, building, and post-processing times required by each technology. These parts include many features (such as holes, thin walls, overhangs, and freeform surfaces), but they are difficult to measure by a CMM.

Jayaram et al. [19] were the first to highlight the need for setting benchmarking standard for AM processes. In their paper, as a first step toward standardization, the authors proposed a benchmark artifact (Fig. 7) simpler than the ones previously described. This part consists of tilted cylinders (to study the effect of tilting features), a stepped cone with four sections of different angles (to investigate stair-stepping) and prismatic boxes (to evaluate the straightness and parallelism of edges and the warpage of flat surfaces). Jayaram et al. produced their benchmark part by four different AM processes: SL, SLS, LOM, and FDM.

Iuliano et al. [20] proposed a benchmark artifact (Fig. 8) to evaluate the AM process accuracy for non-flat surfaces.

Table 1 Summary of benchmark artifacts for geometrical performance evaluation

Paper	Fig.	Year	EVALUATION OF			TESTS	
			Dimensional/ geometrical accuracy	Repeatability	Minimum feature size	Process	Material
[13]	Fig. 1	1991	X			SL	Acrylate
						SLS	PVC, PC
						LOM	Wood-like paper (cellulose)
[14]	Fig. 2	1992	X			SL, SLS, LOM, SGC, FDM	
[15]	Fig. 3	1992	X				
[16]	Fig. 4	1992	X		X		
[17]	Fig. 5	1994	X	X		SL, SLS, FDM, LOM	
[18]	Fig. 6	1994	X			SL, MJ, LOM, FDM, BJ, SLS	
[19]	Fig. 7	1994	X	X		SLS	PC, PA
						SL	5180 resin, 5154 resin
						LOM	
						FDM	Wax
[20]	Fig. 8	1994	X				
[21]	Fig. 9	1995	X			SL	Ciba epoxy resin
						SGC	G-5661 polyester resin
						SLS	PC, PA
						FDM	P200 resin, P300 resin
						LOM	paper
[22]	Fig. 10	1995	X				
[23]		1999					
[24]	Fig. 12	1998	X		X		
[25]	Fig. 13	2000	X			SL	
[26]	Fig.14	2001	X		X	SL, SLS, FDM, LOM	
[27]	Fig. 11	2002	X			FDM	ABS-P400
[28]	Fig. 15	2003	X		X	SL	SL5510(3D Systems)
						FDM	ABS
						SLS	Duraform P/A
						BJ	ZP100 (Z Corp)
						LOM	Paper
[29]	Fig. 25	2003	X	X		BJ	ZP14 (starch-based powder) infiltrated with wax, ZP100 (plaster-based powder) infiltrated with Zi580 (epoxy-based)
[30]		2006					
[31]	Fig. 16	2003	X			FDM	
[2]	Fig. 19	2004	X	X	X	SL	Epoxy resin
[32]						SLS	ProtoForm composite (LNC- 7000), nylon
						FDM	ABS-400
[33]		2006				LOM	Laminated paper
[34]	Fig. 20	2005	X		X	SLS	Polymer coated stainless steel
						SLM	Tool steel, stainless steel 316 L, bronze
[35]	Fig. 22	2005	X		X	BJ	AISI 420 steel
						SLM	AISI 316 L steel, TiAl6V4
[36]	Fig. 23	2005	X			FDM	ABS
[37]	Fig. 24	2006	X			SLS	Aluminum powder with nylon
[38]	Fig. 26	2006	X		X	SLS	LaserForm A6 (steel based), DuraForm (glass filled polyamid), Direct steel DS20 (steel), Direct steel DSH20 (HS steel)
						SLM	CL 20ES (stainless steel), CL 50 WS (hot work steel), CL 40 Ti (titanium), metallic powder, ceramic powder
[39]	Fig. 27	2007	X			SL	SL 5170 photo polymer resin
						SLS	Copper nickel-based EOS Direct Metal-50 powder
[40]	Fig. 28	2007	X			SL	RP Cure 400 ND resin
[41]	Fig. 29	2007	X		X	SLM	Ti-6Al-4 V, Co-Cr-Mo
[42]	Fig. 30	2008	X	X		SL	Resin
[6]	Fig. 31	2008	X		X	SL	Somos 11,120 (epoxy resin), Accura 60, TSR-829
						FDM	ABS, PC/ABS, PC
						MJ	FullCure720 (epoxy resin)

Table 1 (continued)

Paper	Fig.	Year	EVALUATION OF			TESTS	
			Dimensional/ geometrical accuracy	Repeatability	Minimum feature size	Process	Material
						SLS	Duraform PA, Duraform GF, EOS Prime, EOS A
						BJ	102 powder (plaster)
						LOM	OTZ-3LT-P20 (roll paper)
[43]	Fig. 32	2008	X			SLS	DM20 (copper based powder), DS20 (steel based powder)
[44]	Fig. 33	2009	X			SLS	Nylon 12
[45]	Fig. 17	2009	X			FDM	
[46]		2011					
[47]	Fig. 34	2010	X			FDM	ABS-P400
[48]	Fig. 35	2010	X			EBM	Ti-6Al-4 V
						SLM	17–4 stainless steel, 15–5 stainless steel
[49]	Fig. 36	2010	X		X	SLM	18 Ni Marage 300 steel
[50]	Fig. 37	2010	X	X		SLS	Direct Metal 20 (bronze based powder with nickel)
[51]	Fig. 38	2011	X			MJ, SL, SLS, FDM	
[52]	Fig. 39	2011	X	X	X	FDM	ABS
[53]		2014					
[54]	Fig. 40	2012	X			FDM	ABS
[55]	Fig. 41	2012	X	X		SLS	Nylon
[56]	Fig. 43	2012	X		X	SLM, MJ, FDM	
[11]	Fig. 44	2012	X		X	BJ	Starch
						FDM	Polymer
[12]		2014				SLS	Polymer, stainless steel
						SLM	Stainless steel
						EBM	Titanium
[57]	Fig. 18	2013	X			FDM, LOM, SL	
[58]	Fig. 48	2013	X			BJ	Z150 (composite powder) with zb63 binder
[7]	Fig. 49	2013	X			LOM	
						FDM	
[59]	Fig. 45	2014	X			FDM	PLA
[60]	Fig. 50	2014	X	X	X	MJ	
[61]	Fig. 51	2014	X		X	SLS	Sinterstation 2500+
[62]	Fig. 52	2014	X		X		
[63]	Fig. 21	2014	X		X	SLM	Inconel 625
[64]	Fig. 47	2014			X	MJ	VeroWhitePlus RGD835, TangoBlackPlus FLX980
[65]		2015					
[66]	Fig. 42	2015	X	X		FDM	PLA
[67]							
[68]	Fig. 53-55	2015		X	X	SL (based on digital light processing by Texas Instrument)	
[69]	Fig. 56	2015			X	FDM	ABS
[70]	Fig. 57	2015	X			FDM	ABS
[71]	Fig. 58	2015	X		X	SLM	316 L steel
[72]	Fig. 59	2015	X			FDM	ABS
[73]	Fig. 61	2016	X			FDM	ABS
[74]	Fig. 62	2016	X			BJ	Z150 (composite powder) with zb63 binder
[75]						MJ	UV-curable plastic VisiJet M3X
[76]	Fig. 46	2016	X	X	X	MJ	VisiJet CR-WT, VisiJet CR-CL, VeroBlue RGD840
[77]	Fig. 63	2016	X			FDM	ABSplus
						SLM	AlSi10Mg powder
[78]	Fig. 64	2016	X			SLM	316 L steel
[79]	Fig. 60	2017			X	SLM	Aluminum

SL stereolithography, *BJ* binder jetting, *MJ* material jetting, *FDM* fused deposition modeling, *LOM* laminated object manufacturing, *SLS* selective laser sintering, *SLM* selective laser melting, *EBM* electron beam melting, *SGC* solid ground curing

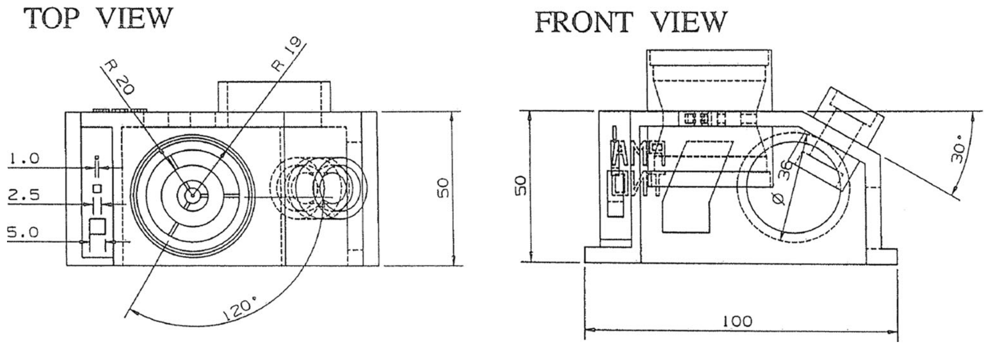


Fig. 1 Benchmark artifact proposed by Kruth [13] (all dimensions are in millimeters)

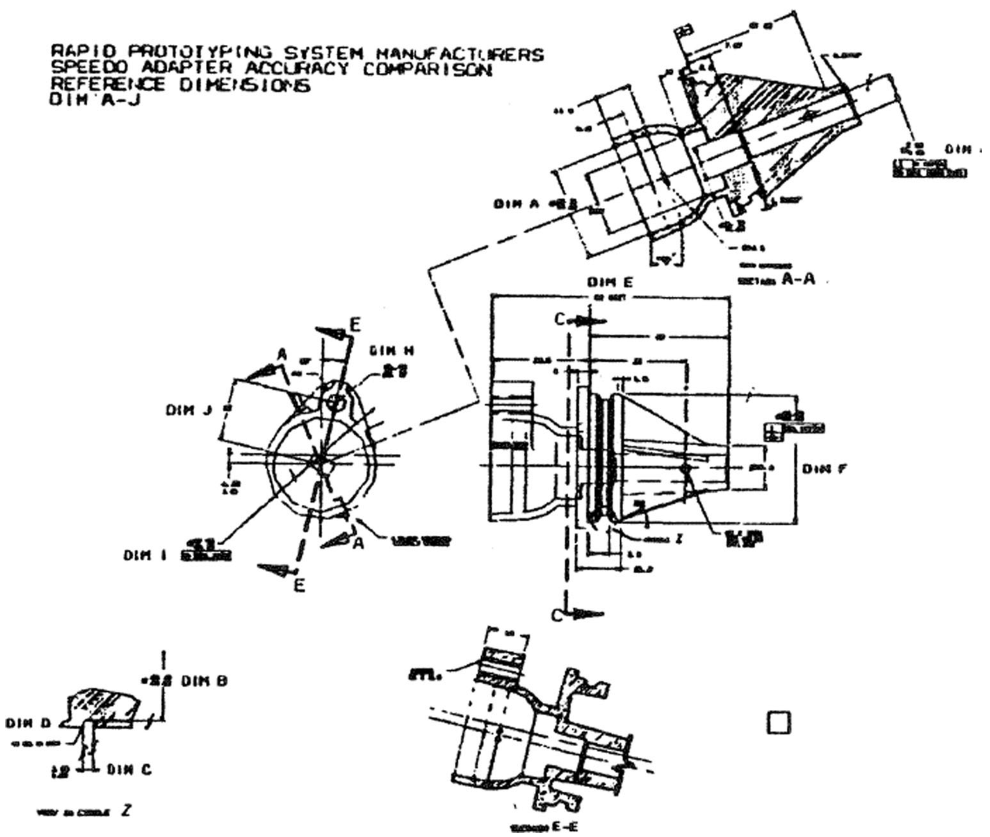


Fig. 2 Benchmark artifact by Chrysler's Jeep and Truck Engineering, reported by Wohlers [14] (overall dimensions = 38 mm × 38 mm × 76 mm)

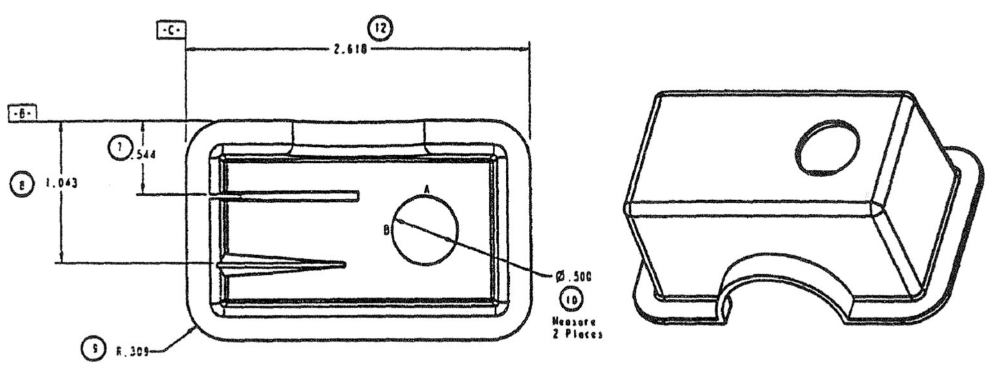


Fig. 3 Benchmark artifact by Eastman Kodak, reported by Van Putte [15]

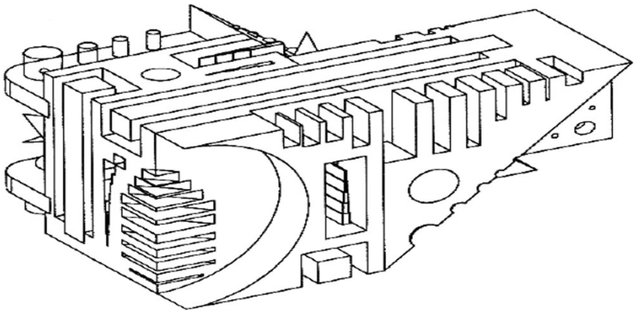


Fig. 4 Benchmark artifact proposed by Lart [16]

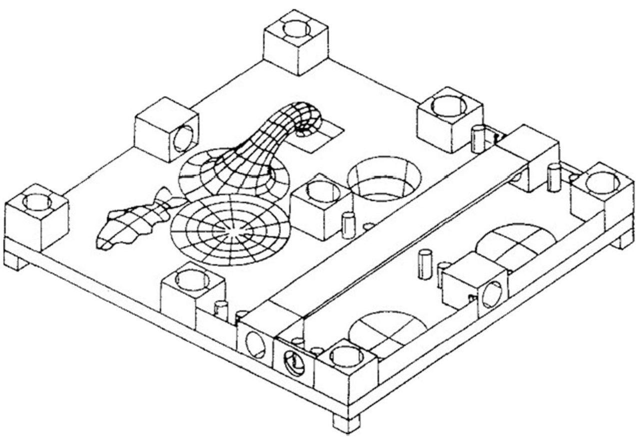


Fig. 5 Benchmark artifact proposed by Childs and Juster [17] (overall dimensions = 240 mm × 240 mm × 40 mm)

However, this part presents some difficulties from the measurement point of view, since it is composed by a cylinder merged with a sphere and appendices extruded toward the inside and outside.

At a later time, the same authors [21] studied the geometrical/dimensional accuracy and the surface roughness obtained with five AM processes (SL, SGC, SLS, FDM, and LOM). In this study, they used an artifact (Fig. 9) proposed by 3D System company, which is a supplier of stereolitography systems. This benchmark part allows an evaluation of dimensions and tolerances according to ANSI-ISO standards, but it is unsuitable to study non-flat surfaces or to determine the minimum feasible feature size.

Two papers by Reeves and Cobb [22] and Shellabear [23] used the same benchmark part (Fig. 10) having only planar surfaces at different angles in the *x*, *y*, or *z* direction. This

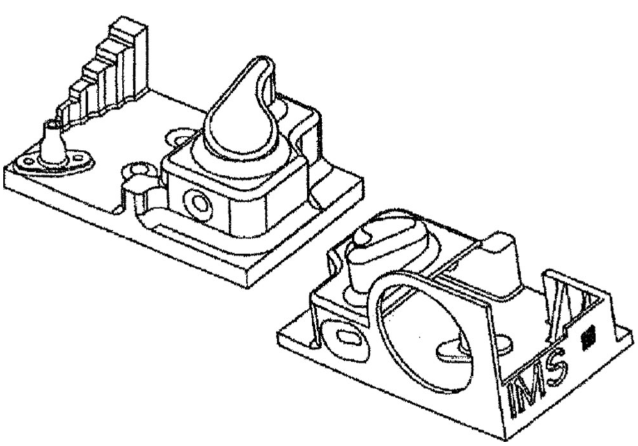


Fig. 6 Benchmark artifacts proposed by IMS [18] (base plate dimensions = 152.4 mm × 101.6 mm)

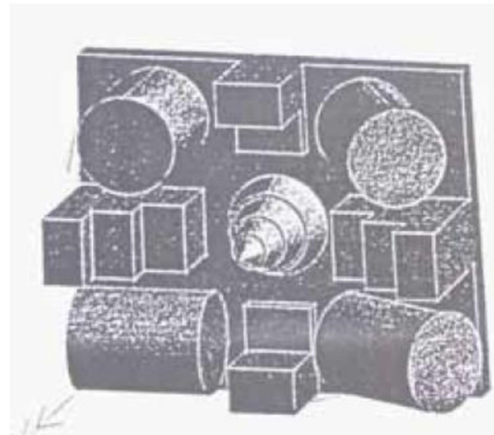


Fig. 7 Benchmark artifact proposed by Jayaram et al. [19]

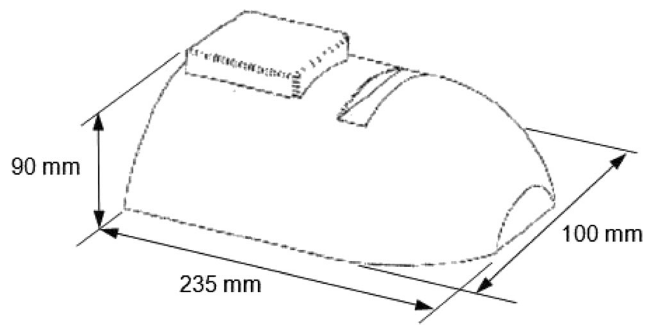


Fig. 8 Benchmark artifact proposed by Iuliano et al. [20]

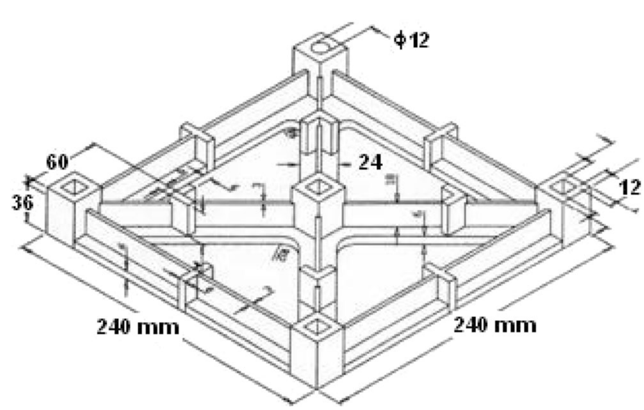


Fig. 9 Benchmark artifact used by Ippolito et al. [21]

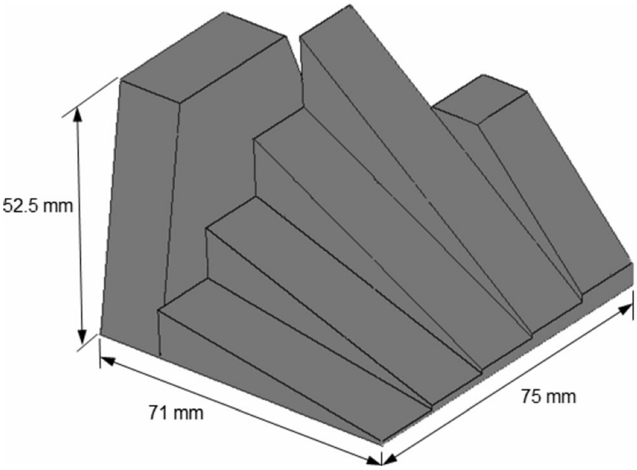


Fig. 10 Benchmark artifact used by Reeves and Cobb [22] and Shellabear [23]

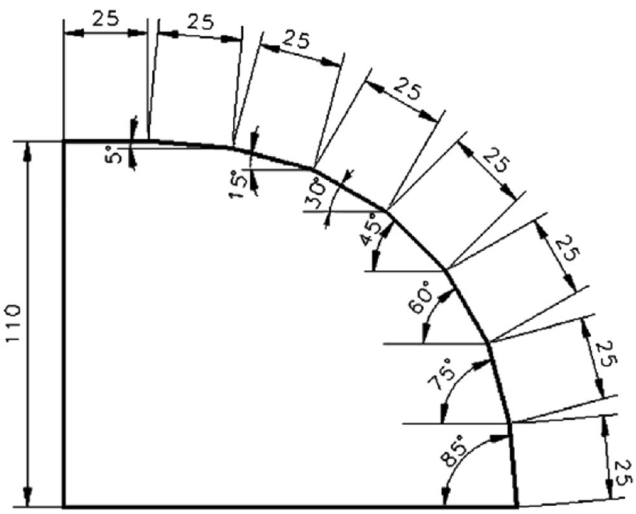


Fig. 11 Benchmark artifact proposed by Perez [27] (all dimensions are in millimeters)

artifact is very easy to measure, but it cannot be used to evaluate circular or curved features.

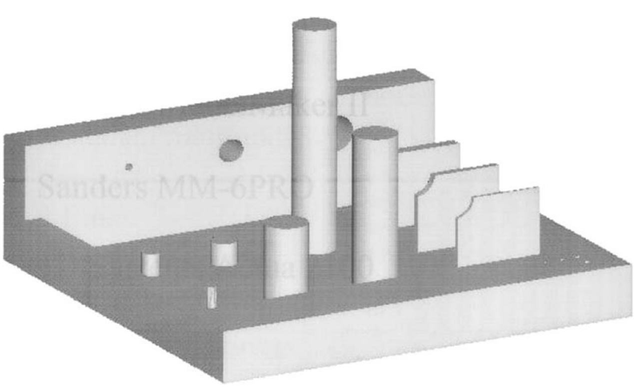


Fig. 12 Benchmark artifact proposed by Loose and Nakagawa [24] (base plate dimensions = 50 mm × 50 mm)

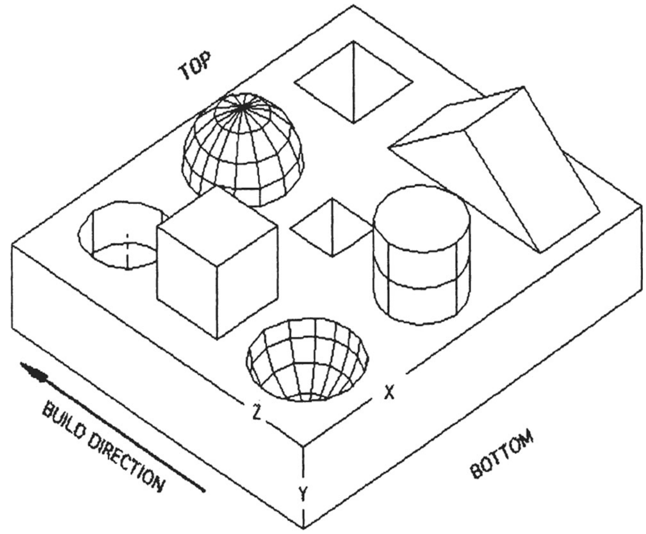


Fig. 13 Benchmark artifact proposed by Zhou et al. [25] (overall dimensions = 36.5 mm × 31 mm × 11.9 mm)

Another benchmark artifact (Fig. 11) comprising only inclined surfaces with different angles was proposed by Perez [27]. This part was used to evaluate the dimensional/geometrical accuracy and surface roughness on pieces produced by FDM.

The benchmark artifact designed by Loose and Nakagawa [24] (Fig. 12) contains very simple small features (cylinders, walls, and holes) and allows to test the process capability to manufacture fine details, in addition to the geometrical/dimensional accuracy.

The benchmark artifact depicted in Fig. 13 was designed by Zhou et al. [25] for a parametric optimization of the SL process, with the aim of improving the part accuracy in terms of dimensional/form errors and surface roughness. Since the

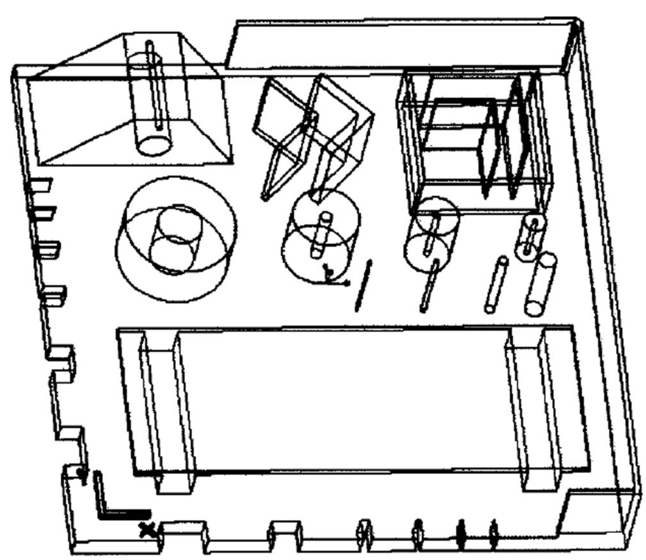


Fig. 14 Benchmark artifact proposed by Xu et al. [26] (base plate dimensions = 100 mm × 100 mm)

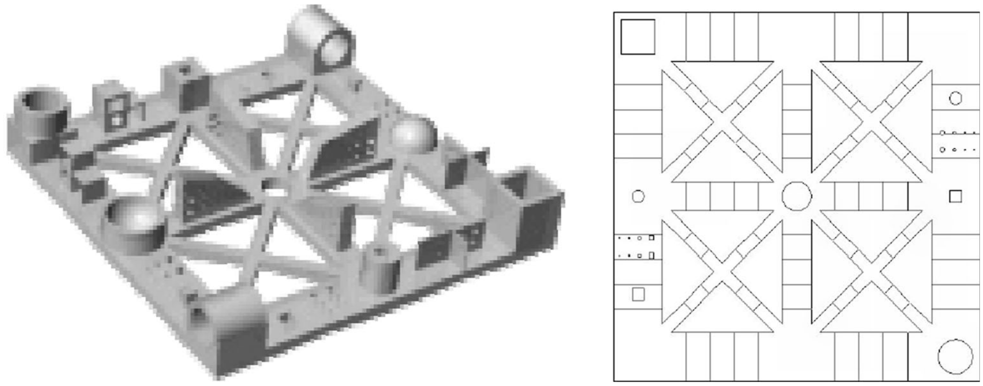


Fig. 15 Benchmark artifact proposed by Byun and Lee (*left*: general view, *right*: detail) [28] (overall dimensions = 150 mm × 150 mm × 25 mm)

distance between features is very small, it is difficult to measure them by a CMM.

The study by Xu et al. [26] investigated the capability of four AM processes (SL, SLS, FDM, and LOM) using a specific benchmark artifact (Fig. 14). This part consists of several features in a range of dimensions (thin wall and holes minimum size = 0.4 mm, gap minimum size = 0.2 mm) to test the process capability to build fine particulars.

Byun and Lee [28] analyzed some of the abovementioned benchmark artifacts [17, 18, 21–25] (Figs. 5, 6, 9, 10, 12, 13) and proposed a new part (Fig. 15) to overcome their drawbacks. As a matter of fact, according to the authors, the existing artifacts:

– were too big or too small, thus leading, in the first case, to an excessive material consumption and the possibility of part warping, or, in the second case, to measurement difficulties and a lack of features with different sizes;
– could not provide robust data by CMM measurement, due to the base surface warping;
– had features only aligned along the *x*, *y* or *z* direction, instead of being arranged along all these directions;
– contained redundant features, causing a waste in time due to their measurement;
– presented freeform features, being difficult to measure.

In their paper, Byun and Lee proposed and applied a design rule to select the necessary arrangements of features along *x*, *y*, or *z* directions. Basing on the obtained feature alignments, they determined the feature positions on the base surface (Fig. 15, left) in order to facilitate the artifact measurement. Moreover, the authors reduced the risk of part warping thanks to the addition of small steps at the base surface bottom (Fig. 15, right) and to a uniform feature distribution (Fig. 15, left).

The benchmark artifact designed by Byun and Lee was used to evaluate the dimensional accuracy, the capability of fabricating fine features and the obtained surface roughness of SL, FDM, SLS, BJ, and LOM.

Another simple benchmark artifact (Fig. 16) was proposed by Grimm [31] to compare three commercial systems for

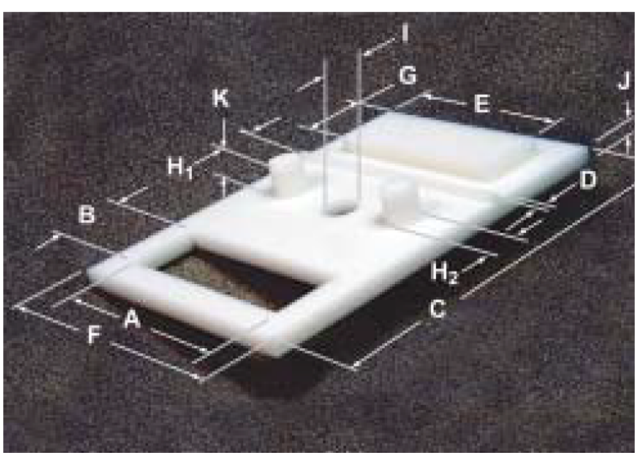


Fig. 16 Benchmark artifact proposed by Grimm [31] (base plate dimensions = 152.4 mm × 101.6 mm)

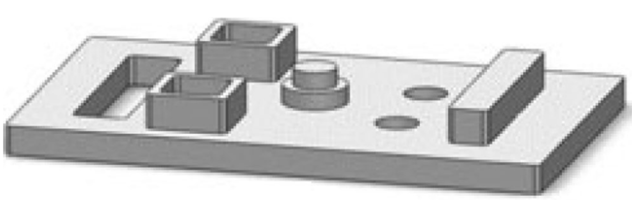


Fig. 17 Benchmark artifact proposed by Espalin et al. [45] and Choi et al. [46]

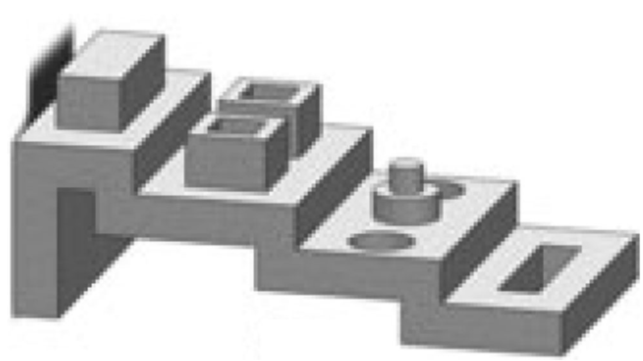


Fig. 18 Benchmark artifact proposed by Roberson et al. [57]

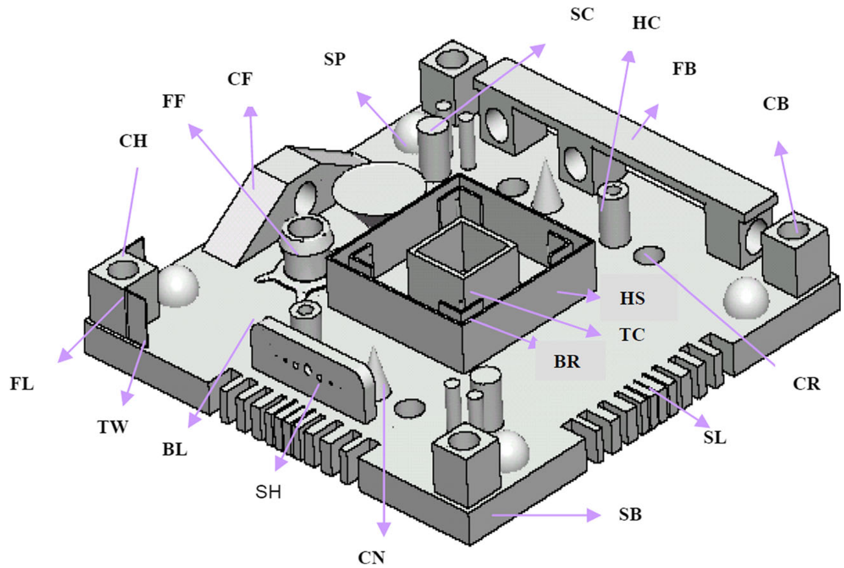


Fig. 19 Benchmark artifact proposed by Mahesh [2, 32, 33] (overall dimensions = 170 mm × 170 mm × 20 mm)

FDM in terms of dimensional accuracy and surface finishing. Some years later, Espalin et al. [45] and Choi et al. [46] used a modified version of Grimm's part (Fig. 17) to evaluate the dimensional accuracy of FDM. This flat artifact was further modified by Roberson et al. [57] for their study of FDM, LOM, and SL processes. The stepped part depicted in Fig. 18 could be used to study the manufacturing of features that need support structures.

Mahesh [2, 32, 33] designed his benchmark artifact (Fig. 19) basing on the analysis of advantages and disadvantages of some parts proposed in past studies [13–23, 26] (Figs. 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 14).

Mahesh stated that a benchmark artifact should cover various aspects, being a multiple purpose test part for a comparative evaluation of AM processes. The author highlighted also that the artifact should contain all typical geometrical features, ranging from solid and hollow cylinders to squares, overhangs, and freeform features, therefore he incorporated all these features in his part. Moreover, Mahesh stated that the artifact should be consistent to standardized measuring techniques, thus he designed several of the part geometrical features for easy reference to the existing ISO standards on geometrical tolerances (e.g., ISO 12780 for straightness, ISO 12781 for flatness, ISO 12180 for cylindricity, and ISO 12181 for roundness). Eventually, the proposed artifact design allowed to evaluate the process repeatability and its capability to manufacture fine features ("SH" small hole diameter 0.5–5 mm, "SL" slot width 0.5–3 mm).

Using this benchmark part, Mahesh performed an extensive study of SL, SLS, FDM, and LOM performances.

Kruth et al. [34] used the benchmark artifact depicted in Fig. 20 to compare five commercial systems for SLS/SLM of metal powders from the point of view of dimensional accuracy, surface roughness, mechanical properties, speed, and repeatability on subsequent parts. The proposed artifact allows to test the feasible resolution of the process by means of small holes/cylinders (diameter 0.5–5 mm) and thin walls (thickness 0.25–1 mm).

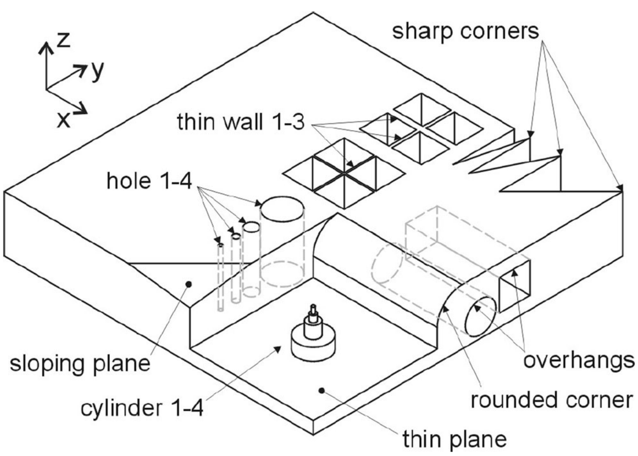


Fig. 20 Benchmark artifact proposed by Kruth et al. [34] (overall dimensions = 50 mm × 50 mm × 9 mm)

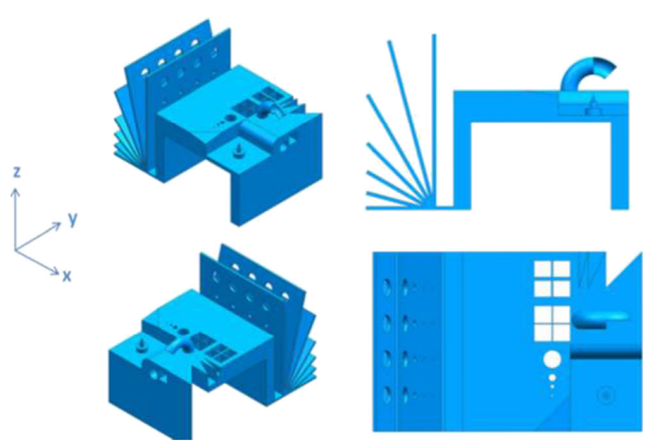


Fig. 21 Benchmark artifact proposed by Yasa et al. [63]

Yasa et al. [63] carried out a comparison between four commercial systems for powder-bed metal fusion process (i.e., SLS/SLM) and they used a modified version (Fig. 21) of the benchmark artifact proposed by Kruth et al. [34] (Fig. 20). In their study, the authors investigated many aspects, namely, dimensional accuracy, surface quality, need for support structures, material density and hardness, process limits (e.g., in terms of minimum wall thickness and inclinations).

Another study focused on AM of metallic materials is the one performed by Castillo [35]. The author designed the benchmark artifact shown in Fig. 22 to investigate the geometrical/dimensional performance of several systems for BJ and SLM. The proposed part allows to test the process accuracy and its capability to produce overhangs, inclined surfaces, thin walls (thickness 0.5–2 mm), high aspect ratio pins (diameter 0.5–5 mm, height 2.5–30 mm), through holes (diameter 0.5–10 mm, depth 5, 10, 100 mm), curved surfaces.

The benchmark artifact proposed by Pennington et al. [36] (Fig. 23) includes six common features, namely, overhangs, horizontal and vertical cylinders, horizontal and vertical bosses, and thin walls. The authors tested the FDM process by printing the test part in two different sizes, the smallest one being a 55% scaled version of the largest one (except for the wall thickness, which was kept constant).

Sercombe and Hopkinson [37] studied the shrinkage of aluminum parts manufactured by SLS and the influence on accuracy of the part position on the machine table. Their benchmark artifact (Fig. 24) is very simple and can be used to evaluate only the linear accuracy.

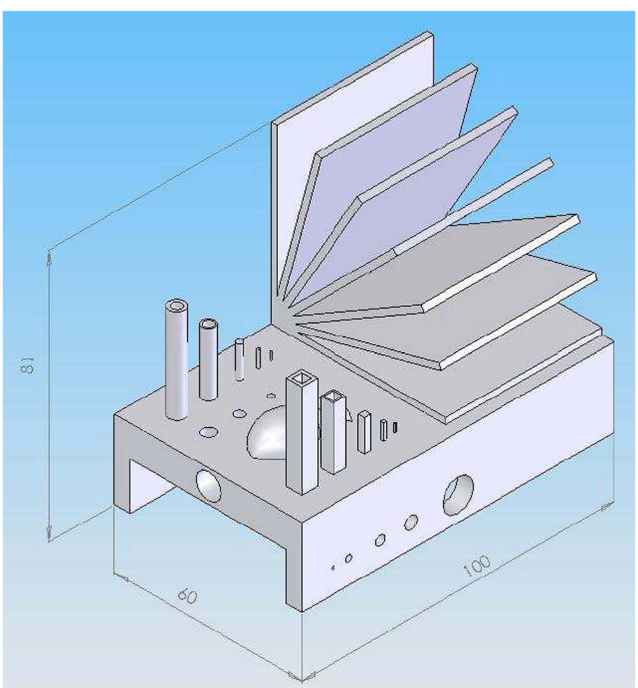


Fig. 22 Benchmark artifact proposed by Castillo [35] (overall dimensions = 60 mm × 100 mm × 81 mm)

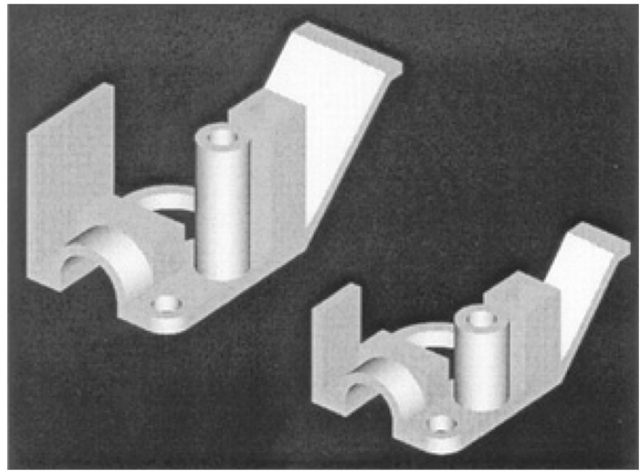


Fig. 23 Large and small version of the benchmark artifact proposed by Pennington et al. [36]

The papers written by Dimitrov et al. [29, 30] develop a procedure to evaluate the BJ process accuracy in accordance to international standards. Basing on the analysis of existing benchmark parts [2, 13, 17, 28, 32] (Figs. 1, 5, 15, 19), the authors stated that a single artifact is not suitable to investigate both dimensional and geometrical accuracy, thus they used two different parts. The first artifact (Fig. 25a) is a cube with slots and protrusions of varying lengths (2, 6, 18, 54, and 162 mm) on three different faces perpendicular to the building axes with the purpose of evaluating the dimensional accuracy of the AM machine with respect to all axes. The second artifact (Fig. 25b) is an actual component (a differential housing) allowing to test the geometrical accuracy of many features, such as freeform, circular, angular, and cylindrical surfaces. Both parts have quite big dimensions, since they have been designed to fill the building volume of the machine used for experiments.

Abdel Ghany and Moustafa [38] compared four commercial systems for metal SLS/SLM using a benchmark artifact (Fig. 26) derived from an actual component, i.e., a half die for

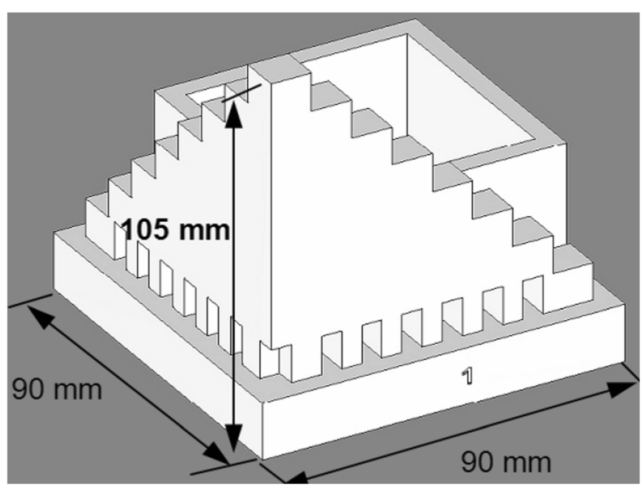


Fig. 24 Benchmark artifact proposed by Sercombe and Hopkinson [37]

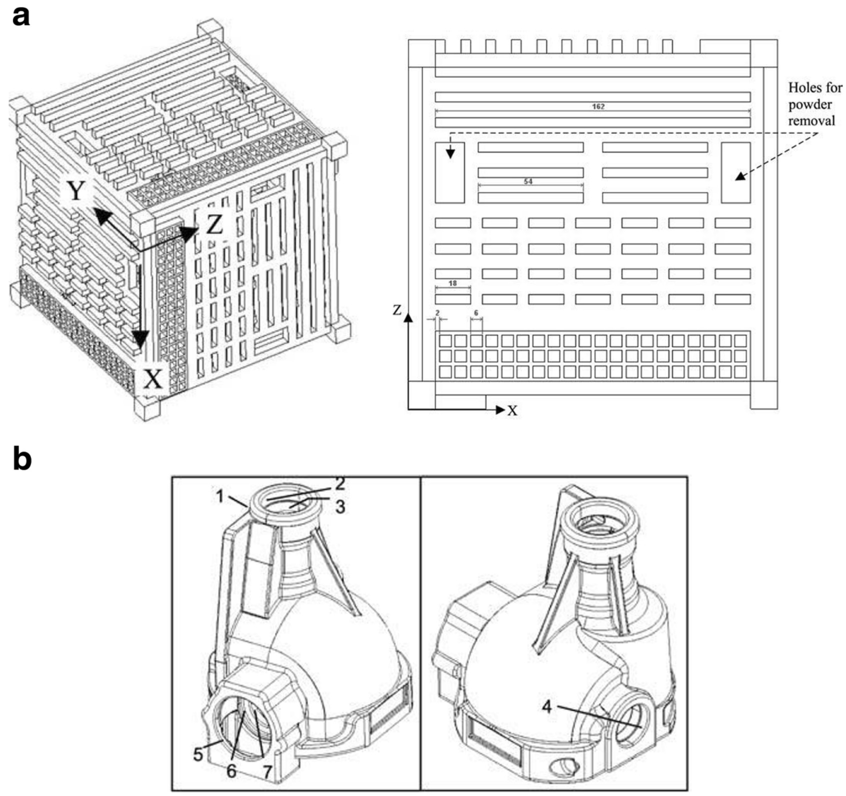


Fig. 25 Benchmark artifacts proposed by Dimitrov et al. [29, 30]. (**a** overall dimensions = 190 mm × 190 mm × 190 mm)

a glass bottle. The selected part comprises many complicated features, such as fine holes and cooling tubes (diameter 0.5–2 mm), curved surfaces, fillets, chamfers, thin walls.

Hanumaiah and Ravi [39] performed an investigation on the straightness, flatness and circularity tolerance estimation from a limited number of sample measurements for SL and SLS processes. For this purpose, the authors designed eight very simple benchmark models (Fig. 27) incorporating the most widely used features, namely, plates, holes, bosses, and ribs.

Campanelli et al. [40] focused on optizimizing the accuracy of products manufactured by SL. Their benchmark artifact (Fig. 28) has features with small and medium dimensions and allows the evaluation of horizontal and vertical dimensional accuracy, form, and position errors.

Vandenbroucke and Kruth [41] designed two benchmark artifacts to study, respectively, the accuracy (Fig. 29a) and the capability to produce fine details (Fig. 29b) of the SLM process. The first part (Fig. 29a) was employed to evaluate the process accuracy along *x*, *y*, and *z* direction, and the accuracy of cylinders and angled features. The second part (Fig. 29b) allowed to check the process resolution with regard to the following features: holes (diameter 0.5–3 mm), slots (thickness 0.5–3 mm), cylinders (diameter 1–5 mm) and thin walls (thickness 0.5–3 mm).

The paper by Scaravetti et al. [42] presents a benchmark artifact (Fig. 30) that can be used not only to investigate the process accuracy but also to link the observed defects to machine or material issues, avoiding the production of several specimens. In order to reduce the manufacturing time, the feature number is optimized to have the smallest base surface, preserving the minimum feature distance to allow CMM

Fig. 26 Benchmark artifact proposed by Abdel Ghany and Moustafa [38] (overall dimensions = 200 mm × 100 mm × 40 mm)

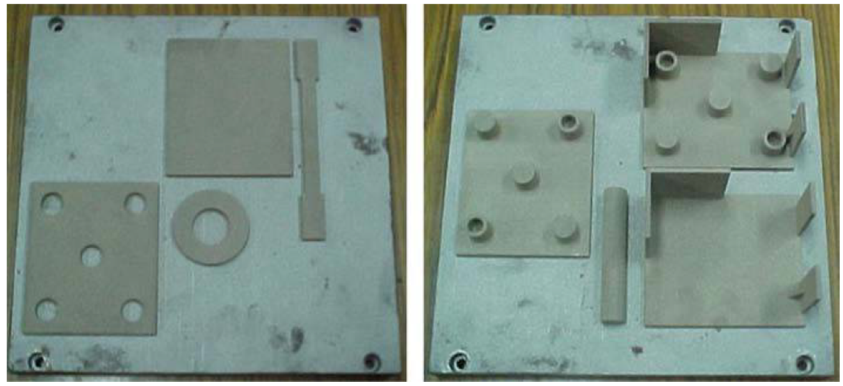


Fig. 27 Benchmark artifacts proposed by Hanumaiah and Ravi [39]

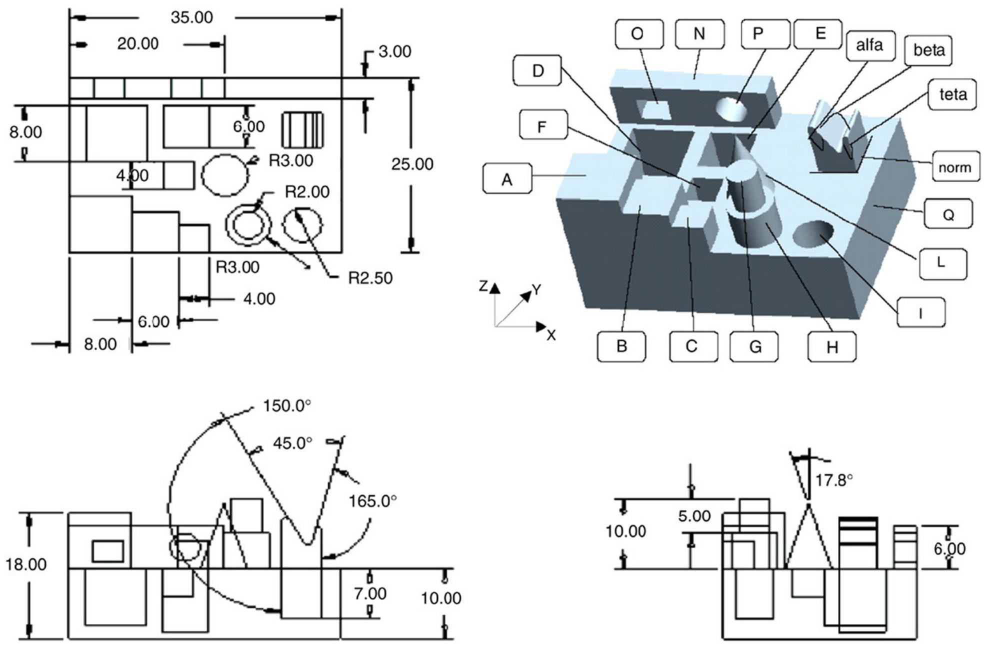


Fig. 28 Benchmark artifact proposed by Campanelli et al. [40]

measurements. The base plate is very thin but has a special design to avoid warping.

Kim and Oh [6] performed an extensive investigation on several AM processes (SL, SLS, MJ, BJ, FDM, and LOM) taking into account mechanical properties (e.g., tensile and compressive strengths, hardness, impact strength, and heat resistance), surface roughness, geometrical and dimensional accuracy, manufacturing speed, and material costs. The authors proposed two benchmark artifacts to evaluate the process accuracy (Fig. 31a, b), two parts to study the feasibility of fine features (Fig. 31c, d) and evaluated the surface finishing through an artifact (Fig. 31e) similar to the one used by Reeves and Cobb [22] and Shellabear [23] (Fig. 10). The part of Fig. 31a contains basic features, such as small holes, ribs,

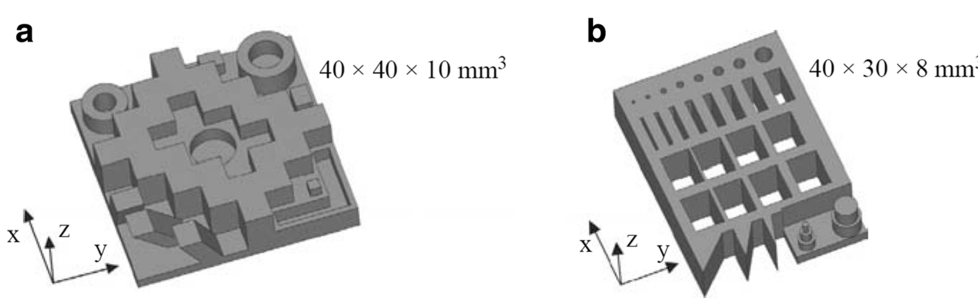


Fig. 29 Benchmark artifacts proposed by Vandenbroucke and Kruth [41]

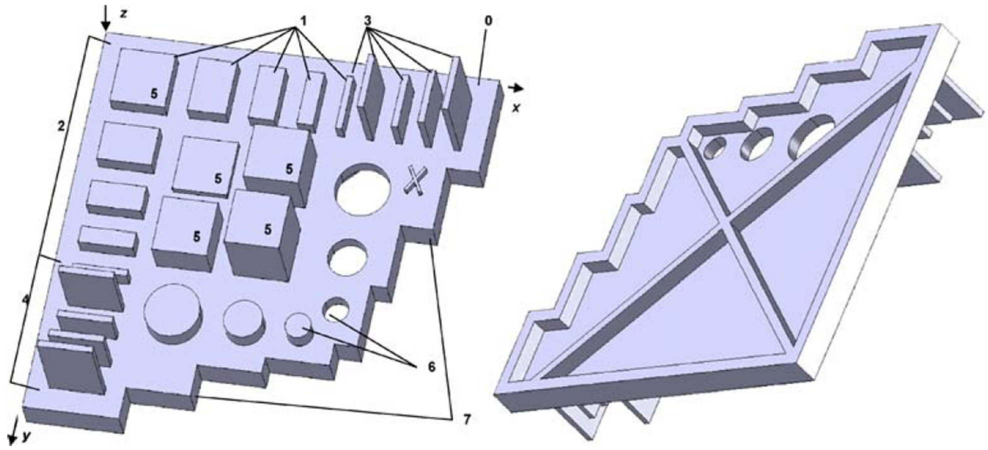


Fig. 30 Benchmark artifact proposed by Scaravetti et al. [42] (base plate dimensions = 122 mm × 122 mm)

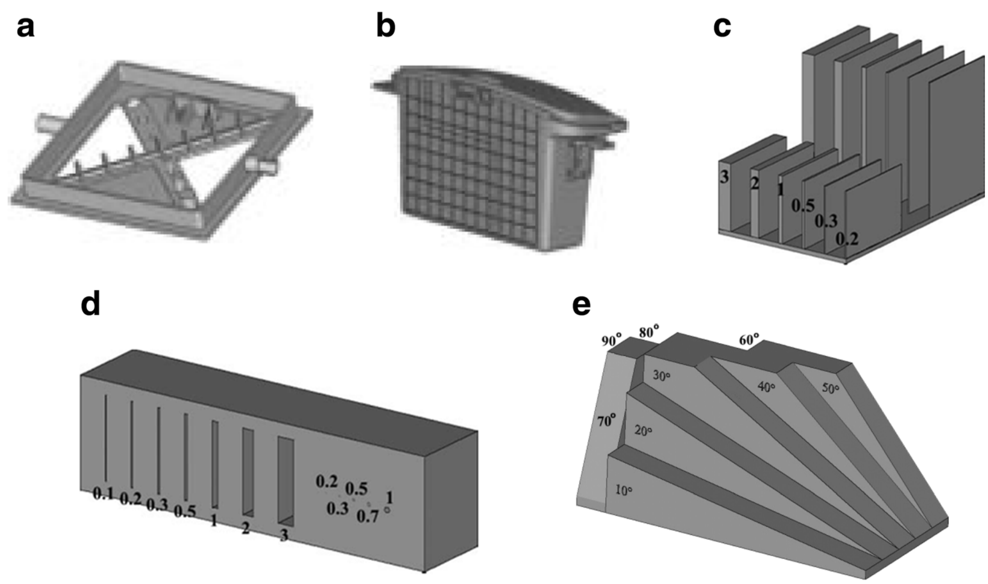


Fig. 31 Benchmark artifacts proposed by Kim and Oh [6] (overall dimensions: (a) = 237.5 mm × 200 mm × 24 mm, (b) = 213.2 mm × 80.7 mm × 123.5 mm, e) = 50 mm × 100 mm × 45 mm)

and bosses, and is mainly planar, thus it could be affected by warpage issues. The part depicted in Fig. 31b is more complex, being made by 15 subparts, and is recommended to check the assembly facility and the geometric accuracy after assembly.

The study of Pessard et al. [43] aims to evaluate if the accuracy of SLS process is suitable for manufacturing die casting molds. For this purpose, they took into account a part containing the typical features of components made by die casting and designed a benchmark artifact (Fig. 32), half of which had the part shape while the other half represented the respective mold.

Kotlinski et al. [44] focused on the dimensional/geometrical accuracy assessment of machine parts produced by SLS. For this aim, they designed a benchmark artifact (Fig. 33) containing the most frequent features in this kind of parts, such as holes, shafts, planes, and channels.

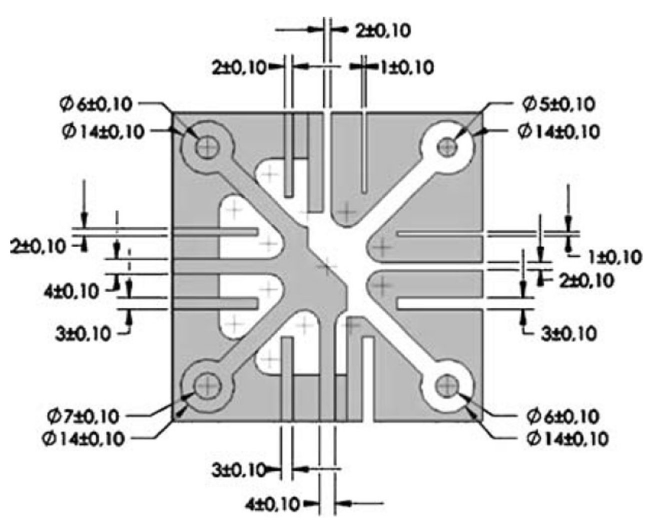


Fig. 32 Benchmark artifact proposed by Pessard et al. [43] (all dimensions are in millimeters)

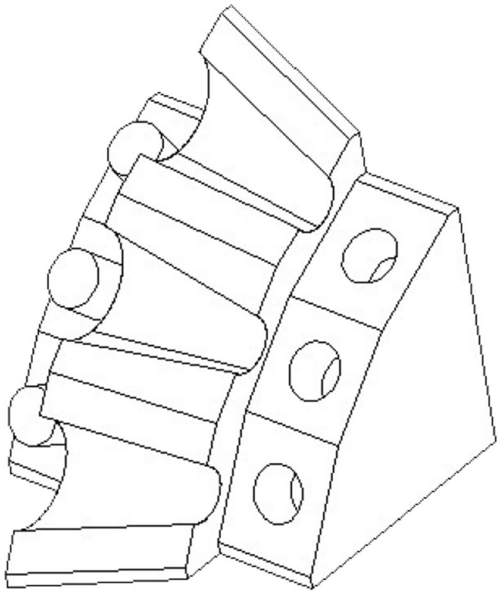


Fig. 33 Benchmark artifact proposed by Kotlinski et al. [44]

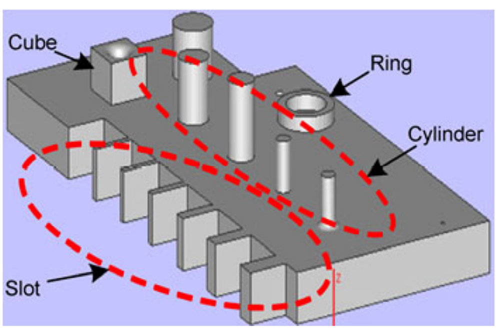


Fig. 34 Benchmark artifact proposed by Bakar et al. [47]

Bakar et al. [47] designed a benchmark artifact (Fig. 34) that they used to optimize several FDM process parameters, evaluating dimensional accuracy and surface finishing. The proposed part includes typical features in different sizes, but not so small to be at the feasibility limit (slot wall thickness 1.5–5 mm).

Similarly to Jayaram et al. [19], Cooke and Soons [48] underlined the importance of developing standardized test methods for the performance characterization of AM processes. As a first step, they investigated EBM and SLM accuracy using the NAS 979 circle-diamond-square with an inverted cone (Fig. 35) from Aerospace Industries Association (AIA) /National Aerospace Standard [80]. This part, without the inverted cone, was originally designed to test CNC machines in terms of dimensions, flatness, squareness, parallelism, angular deviation, circularity, and surface finish. The NAS 979 test part was selected by the authors to compare the geometric errors of AM and machining, but it does not allow to point out the error sources (e.g., machine or process) or to find the performance limits for fine features. For this reason, Cooke and Soons did not propose this artifact as a standard for testing AM process.

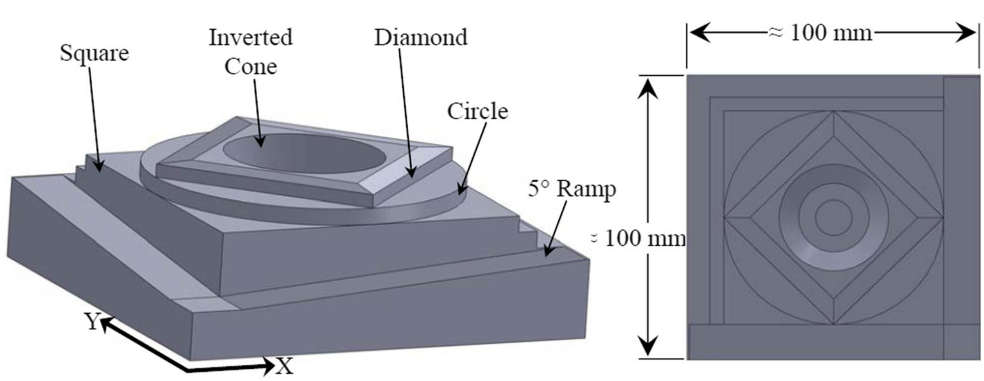
Figure 36 depicts the benchmark artifact proposed by Campanelli et al. [49] to evaluate the SLM process capability in terms of dimensional accuracy and minimum feasible feature size. The part features are cylindrical holes (“CH”), cylindrical extrusions (“CE”), vertical holes (“VH”), parallelepiped extrusions (“PE”), parallelepiped cavities (“CE”), and thin walls (“TW”) with a diameter/thickness/width range of 0.2–6 mm.

Delgado et al. [50] focused their study on assessing the dimensional and geometrical repeatability of SLS process. They designed a very simple benchmark artifact (Fig. 37a) and placed it in different positions within the machine building platform (Fig. 37b).

The study of Brajlih et al. [51] had the aim of setting a quick and simple method to evaluate different AM technologies. Therefore, the authors designed a specific benchmark artifact (Fig. 38) that was easy to produce on the different machines subject to comparison, allowed the accuracy testing and was quick to measure by either contact or non-contact techniques. Brajlih et al. used their part to test systems for MJ, SL, SLS, and FDM processes.

Johnson et al. [52, 53] designed the first specific benchmark artifact (Fig. 39) for the quantitative evaluation of the performance of an open source FDM system. The proposed

Fig. 35 Benchmark artifact used by Cooke and Soons [48] (*left*: 3D view, *right*: top view)



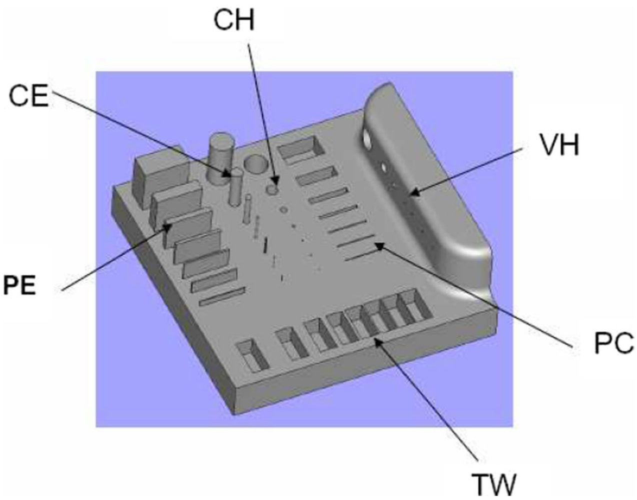


Fig. 36 Benchmark artifact proposed by Campanelli et al. [49] (overall dimensions = 70 mm × 70 mm × 25 mm)

test part allows the assessment of the dimensional accuracy, feature size, and geometry limitations; geometric and dimensional tolerances, and repeatability even within the relatively small building platform of the selected FDM system. The artifact comprises several geometries, including inclined overhangs and features with a range of dimensions ("XW" and "YW" thin wall thickness 1–2 mm, "XN" and "YN" square notch width 1.5–4 mm) to test the process resolution.

Saqib and Urbanic [54] used a simple benchmark artifact with thick and thin walls (Fig. 40) to study the effect of FDM process parameters (i.e., layer thickness, part position in the building platform, and part orientation) on the part flatness, cylindricity, and perpendicularity.

Fahad and Hopkinson [55] highlighted the need of repeated features, in order to assess not only the process accuracy but also its repeatability. Therefore, the authors designed a benchmark (Fig. 41) consisting of three sections with symmetrically repeated features, thus avoiding the need of building several part for the repeatability evaluation. In their studies on the evaluation of an open-source 3D printer [66, 67], Lanzotti et al. modified this benchmark artifact placing the three feature series side by side (Fig. 42), in order to allow the part fabrication in the same printing and the laser scanner acquisition.

The paper by Williams and Seepersad [56] presents some examples of benchmark artifacts designed by students of a course on additive manufacturing, aiming at accuracy (Fig. 43a) or resolution (Fig. 43b) evaluation. However, the authors just state that the proposed parts have been manufactured by SLM, MJ, and FDM, but they do not comment on the experimental results.

Moylan et al. [11, 12] from the the US National Institute of Standards and Technology (NIST) performed an extensive investigation of existing benchmark artifacts to highlight their strengths and weaknesses. Based on the results of their

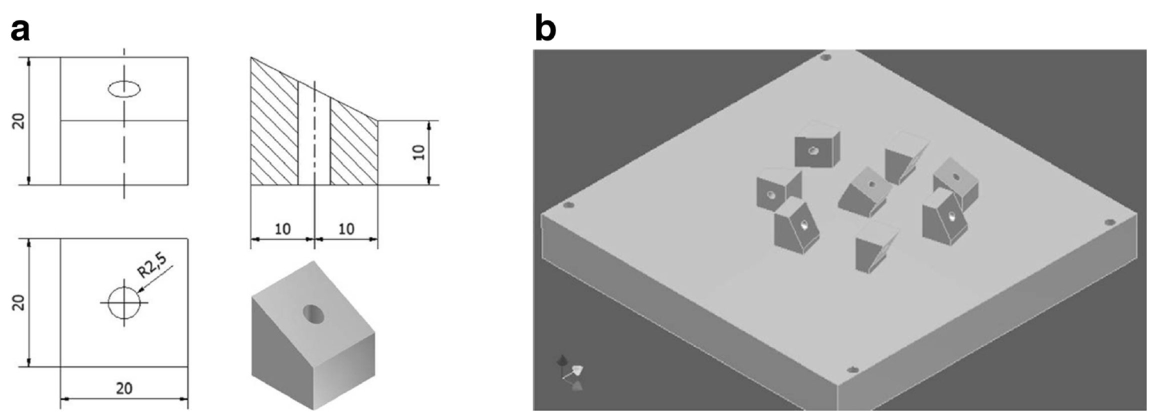
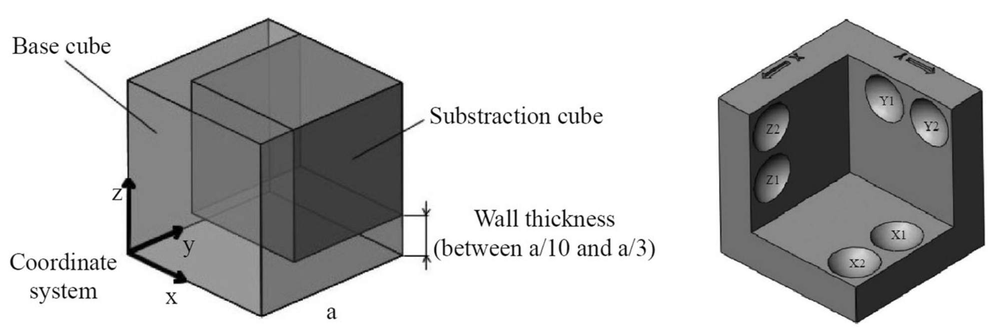


Fig. 37 **a** Benchmark artifact proposed by Delgado et al. [50] (all dimensions are in millimeters). **b** Artifact positions in the building platform

Fig. 38 Benchmark artifact proposed by Brajlih et al. [51] (*a* = 30 mm, sphere diameter *D* = a/3)



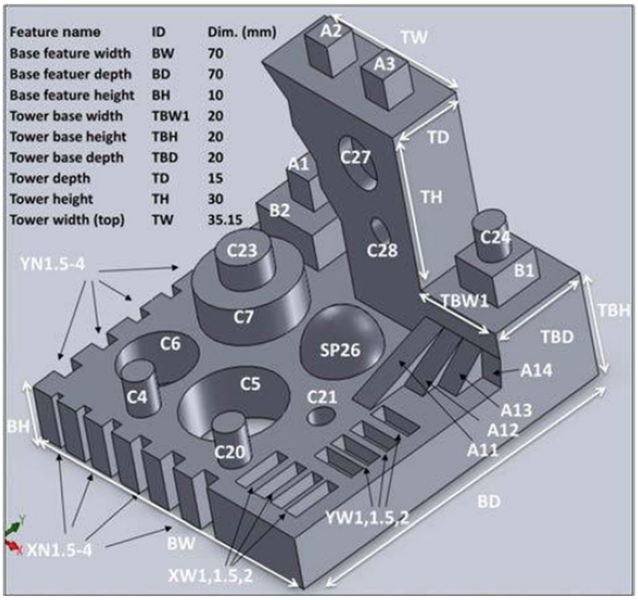


Fig. 39 Benchmark artifact proposed by Johnson et al. [52, 53]

literature analysis and their knowledge of test parts for machining processes [48] (Fig. 35), the authors proposed their own standardized artifact (Fig. 44). This test part is designed for the characterization of the process capabilities and limitations and for linking the measured errors measured to specific sources in the AM system. With regard to the system resolution, there are two sets of fine features: rectangular bosses/holes and circular pins/holes (width/diameter 0.25–2 mm). The first set also allows to establish the minimum distance between features, in addition to the minimum feature size. The proposed artifact was built in many materials using several AM technologies (BJ, FDM, SLS, SLM, and EBM).

A modified version (Fig. 45) of NIST benchmark artifact [11, 12] (Fig. 44) was used by Cruz Sanchez et al. [59] in their study on the performance evaluation of an open source FDM system. The author modified the original test part introducing all the suitable features to evaluate the dimensional accuracies of the investigated machine. The fine features of this artifact have bigger dimensions (pin diameter 2–4 mm, thin wall thickness 1.5–3 mm, notch width 1.5–4 mm) than in the NIST part.

More recently, Yang et al. [76] modified the NIST benchmark artifact [11, 12] (Fig. 44) to evaluate the accuracy, repeatability, and dimensional limitations of a MJ system. The new test part (Fig. 46) has reduced overall dimensions and contains more complex features to evaluate the process performance along different building directions. Moreover, this artifact includes identical features to assess the process accuracy and repeatability, while its fine features (diameter/width 0.25–1.25 mm) are used to find the minimum feasible feature size.

In their study on MJ process, Meisel and Williams [64, 65] proposed two benchmark artifacts to evaluate the minimum feasible feature size (Fig. 47a) and the maximum angle in case of inclined surfaces without support structures (Fig. 47b). Regarding the first aim, the authors took into account the NIST test part [11, 12] (Fig. 44) and, in particular, its fine features devoted to the resolution assessment. The new specific part designed by Meisel and Williams (Fig. 47a) includes the same features, but with smaller dimensions (circle diameter/rectangle width 0.1–2 mm, rectangle length 0.3–6 mm).

Islam et al. [58] focused on assessing the accuracy of BJ process only in terms of error on linear dimensions and hole diameters. Thus, they designed a very simple U-shaped benchmark artifact with a cylindrical hole (Fig. 48).

A review of existing benchmark artifacts [2, 11, 12, 17, 25, 32, 33, 57] (Figs. 5, 13, 18, 19, 44) inspired the design by Perez et al. [7] (Fig. 49), containing both positive features (i.e., protruding above the base surface) and negative features (i.e., expanding below the base surface). In contrast with Mahesh's part [2, 32, 33] (Fig. 19), the artifact by Perez et al. does not include overhangs to avoid the use of support structures, whose removal may affect the measured features.

Hao et al. [60] designed a benchmark artifact (Fig. 50) to study the manufacturing of micro- and meso-scale features through AM processes. This test part is significantly smaller compared to the existing artifacts and includes several basic features with the same geometries and different aspect ratios, to investigate the capabilities and limitations of the AM processes of creating these features within the desired accuracy level. The artifact design includes identical features to assess the process repeatability. The micro-scale features have sizes down to 40 µm in x and y directions and down to 80 µm in z direction.

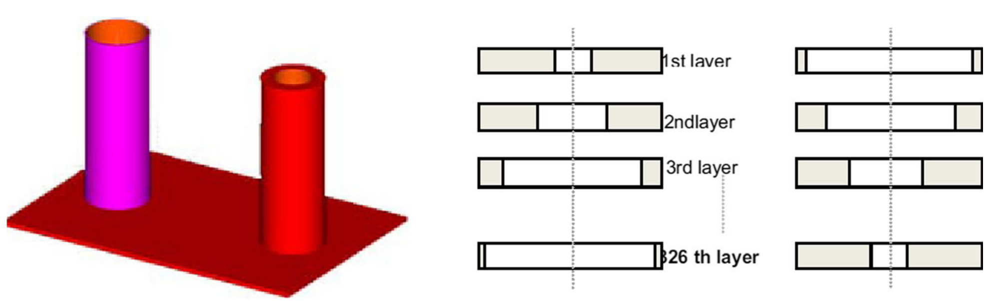


Fig. 40 Benchmark artifact proposed by Saqib and Urbanic [54] (cylinder height = 100 mm, base plate dimensions = 150 mm × 75 mm × 3 mm)

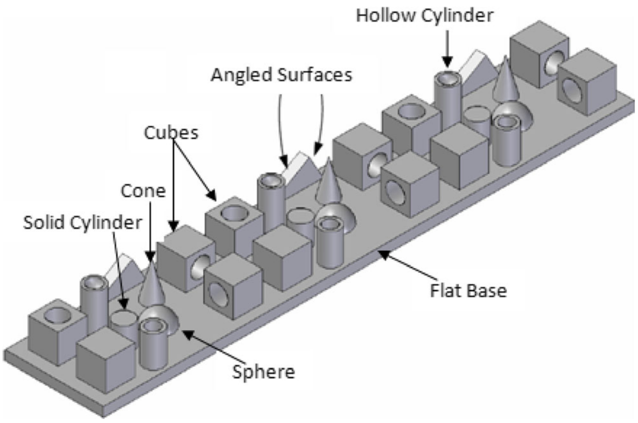


Fig. 41 Benchmark artifact proposed by Fahad and Hopkinson [55] (base plate dimensions = 270 mm × 50 mm)

Fig. 42 Benchmark artifact used by Lanzotti et al. [66, 67]

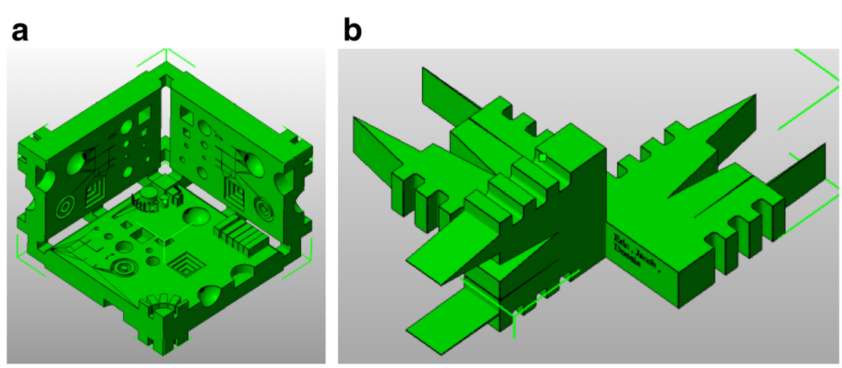
Yang and Anam [61] analyzed the efficiency of some benchmark artifact designs for the evaluation of AM process performance [2, 6, 11–13, 17, 21, 26, 32, 33, 35, 38, 42, 48, 52, 53, 55] (Figs. 1, 5, 9, 14, 19, 22, 26, 30, 31, 35, 39, 41, and 44). In particular, they focused on the NIST standard test part (Fig. 44) and concluded that it had to be redesigned since several geometrical characteristics appeared to be redundant, and both the feature size and orientation should be taken into account in the geometrical accuracy assessment. The benchmark artifact proposed by Yang and Anam (Fig. 51) is easy to access by typical measurement systems (such as micrometers, CMM, and optical microscopes) and enables the evaluation of dimensional accuracy, straightness/flatness, parallelism, true position, surface finish, and minimum feature size.

Jared et al. [62] designed two benchmark artifacts to test, respectively, the dimensional accuracy (Fig. 52a) and the minimum feasible feature size (Fig. 52b) of AM processes. The so-called “Manhattan” test part (Fig. 52a) consists of square columns with the same base size and different heights for accuracy measurement at various positions in space. The second test part (Fig. 52b) is a 3D eight-sided version of the “Siemens star” target design for 2D imaging systems. In the preliminary work described in [62], the benchmark artifacts were just printed by a FDM machine, but no measurements were performed.

The paper by Thompson and Mischkot [68] is focused on AM technologies at the micro-scale and presents the iterative design process of a benchmark artifact to investigate the process resolution and repeatability. During the test part evolution (Figs. 53, 54 and 55) the total number of test features per part, the number of test feature set per part, the spacing between features and the part functionality increased, while the coupling in the part decreased. The final design is a set of three parts (Fig. 55) with feature variations in x, y, and z axis, respectively. The features of the parts in Fig. 55a, b have, respectively, dimensions $X \times 200 \times 100$ μm and $200 \times Y \times 100$ μm where X and Y varies from 5 to 100 μm in increments of 5 μm. The features of the part in Fig. 55c have dimensions $200 \times 200 \times Z$ μm where Z varies from 5 to 68 μm in increments of 1 μm or 5 μm.

Chang et al. [69] proposed some benchmark artifacts (Fig. 56) that are unique and complementary to those already existing, with the aim of investigating the dimensional limitations of AM processes. These parts, named as Geometric Element Test Targets (GETTs), are the 3D translation of 2D test artifacts for printing systems and rely on the positioning and spatial frequency of geometric features (lines, angles, and circles) to point out the process

Fig. 43 Benchmark artifact reported by Williams and Seepersad [56]



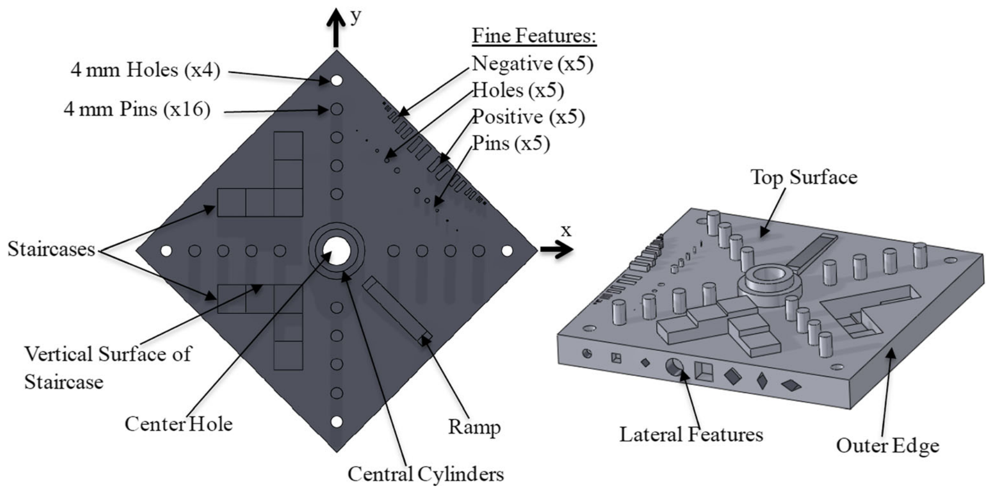


Fig. 44 Benchmark artifact proposed by Moylan et al. [11, 12] (base plate dimensions = 100 mm × 100 mm × 10 mm)

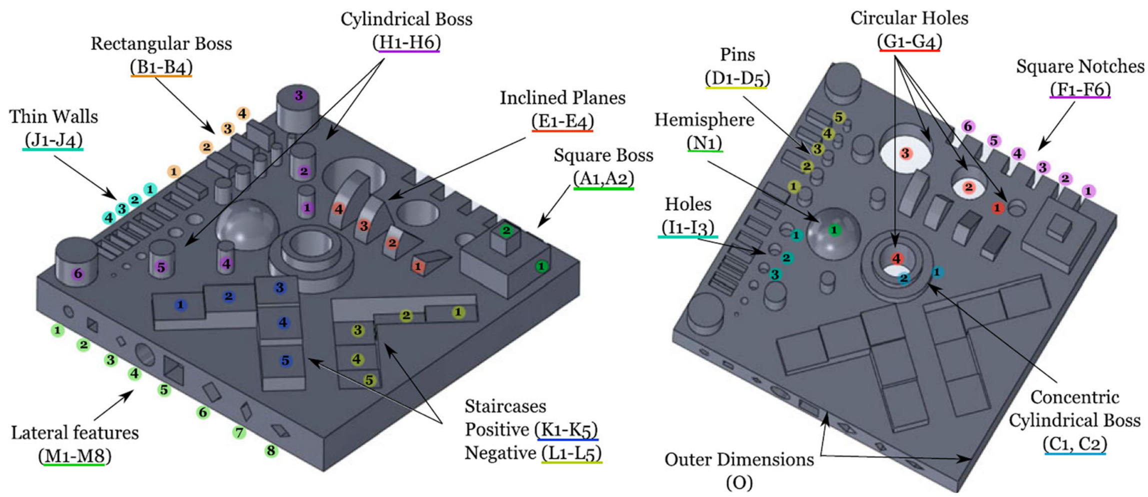


Fig. 45 Benchmark artifact proposed by Cruz Sanchez et al. [59] (base plate dimensions = 90 mm × 90 mm × 10 mm)

resolution based on the occurring failures. A remarkable characteristic of these test parts is that the failures can be inspected visually, prior to further measurement by contact or non-contact measurements. The proposed GETTs were tested manufacturing them by FDM with different feature sizes and spatial frequencies.

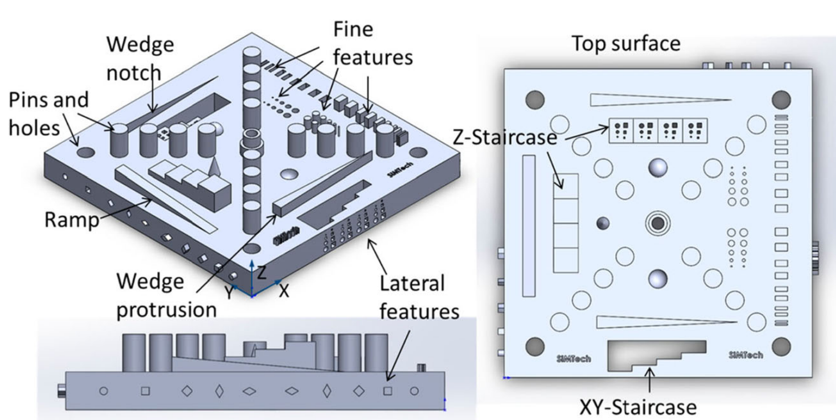


Fig. 46 Benchmark artifact proposed by Yang et al. [76] (overall dimensions = 50 mm × 50 mm × 10 mm)

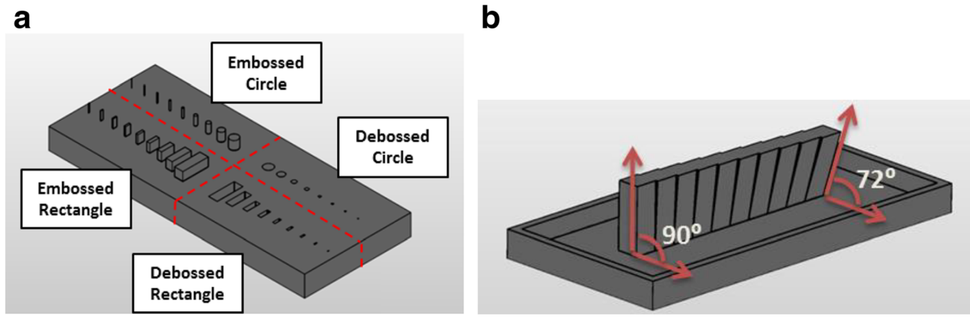


Fig. 47 Benchmark artifacts proposed by Meisel and Williams [64, 65] to assess **a** minimum feature size and **b** maximum self-supporting angle

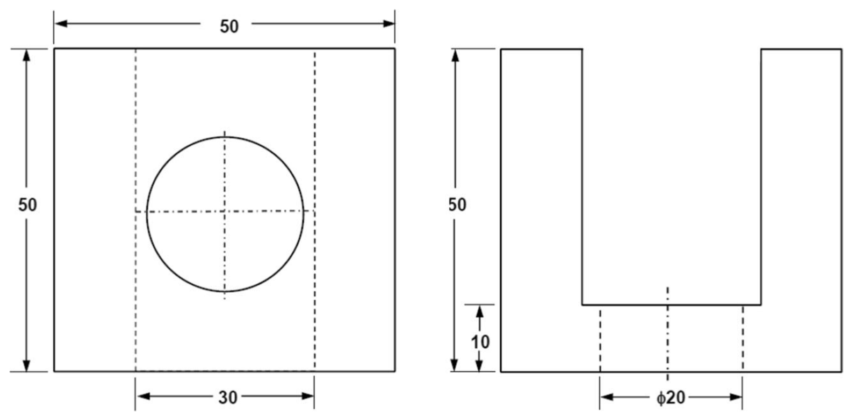


Fig. 48 Benchmark artifact proposed by Islam et al. [58] (all dimensions are in millimeters)

Decker and Yee [70] state that the existing complex benchmark artifacts require a lot of time and material to produce, but a remarkable part of their volume is not used to evaluate the dimensional/geometrical accuracy. For this reason, the authors proposed a small test part (Fig. 57) for the FDM dimensional accuracy assessment, which reduces manufacturing time and material usage, and can be measured quickly and easily. The proposed artifact was compared with the two parts designed by Moylan et al. [11, 12] and Grimm [31], proving to be the best in terms of mass, print time, volume, and volume percentage dedicated to measurable test features, even if it has a smaller feature quantity. Such a small benchmarking object may be useful to assess the dimensional accuracy variation within the machine table if printed in various locations.

The benchmark artifact in Fig. 58 has been designed by Teeter et al. [71] to assess the SLM performance. The authors

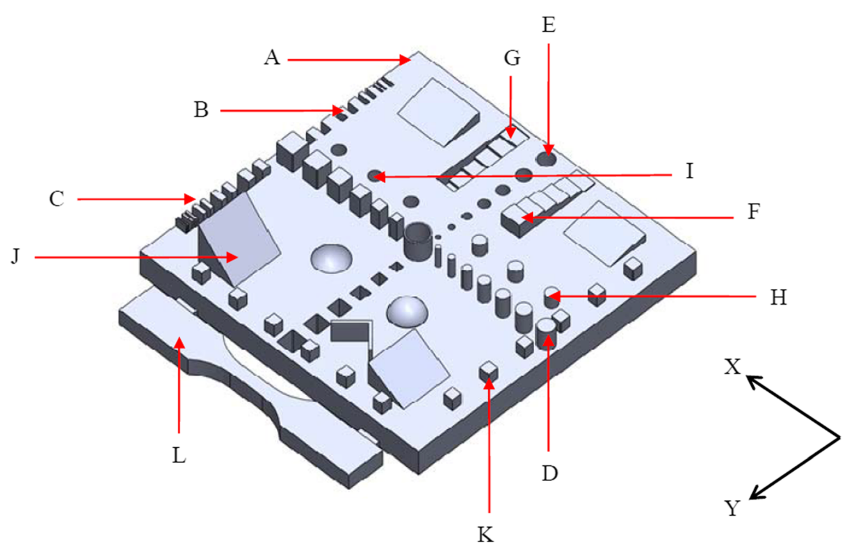


Fig. 49 Benchmark artifact proposed by Perez et al. [7]

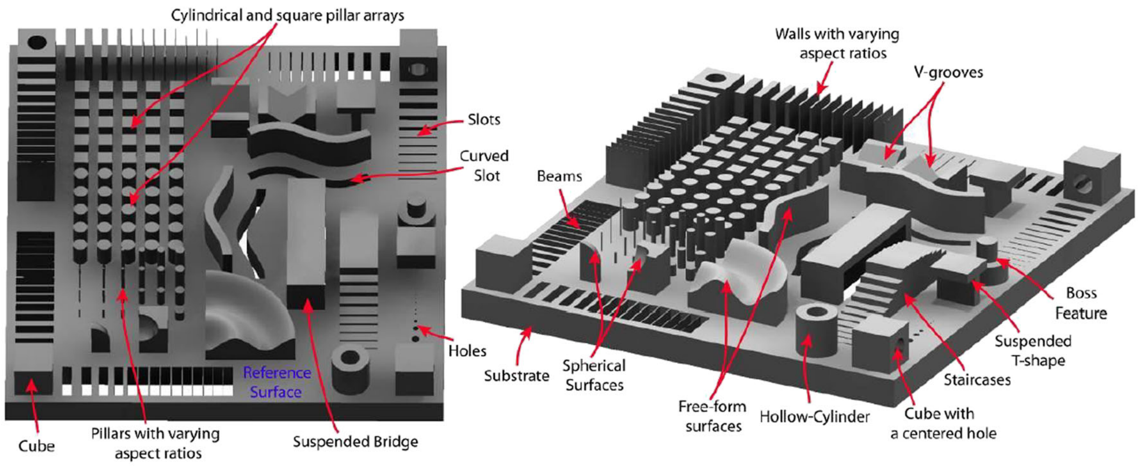


Fig. 50 Benchmark artifact proposed by Hao et al. [60] (base plate dimensions = 46 mm × 50 mm × 3 mm)

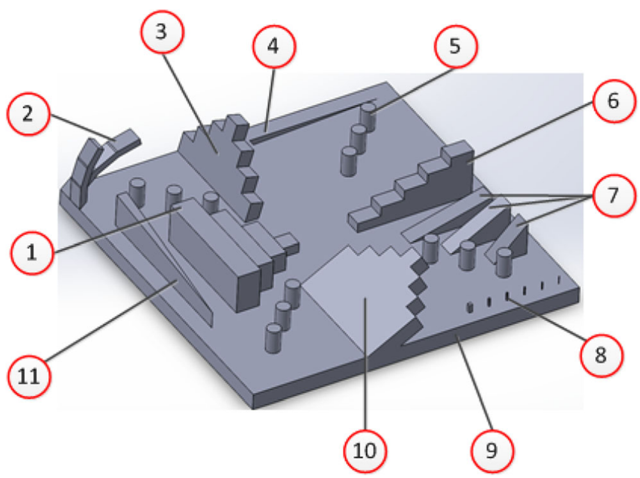


Fig. 51 Benchmark artifact proposed by Yang and Anam [61] (base plate dimensions = 100 mm × 100 mm)

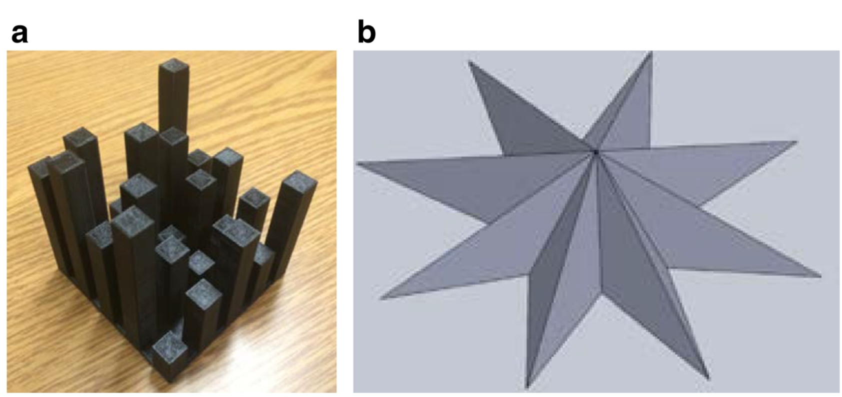
focused on objects that could be relevant to medical applications and created their test part including a range of features with different dimensions (hole/cylinder diameter 0.3–8 mm, rectangle thickness 0.1–1 mm, open cylinder thickness 0.1–0.6 mm, gaps: 0.1–1 mm, lattice wall thickness: 0.3, 0.4, 0.6, and 0.8 mm). The feature positions were specifically set to allow measurements. The benchmark artifact was replicated and mirrored, placing it in the four corners and in the center of the machine building platform in order to study the effect of the part position.

Fernandez-Vicente et al. [72] designed three benchmark artifacts to investigate the FDM limitations in generating features such as overhangs (Fig. 59a), angled surfaces (Fig. 59b) and bridges (Fig. 59c). The overhang length (L_o in Fig. 59a) was varied from 0.5 to 11.5 mm in steps between 0.1 and 0.5 mm, while the overhang thickness (H_o in Fig. 59a) had the following values 0.4, 0.8, 1.2, and 5 mm. The tested angles (β_a in Fig. 59b) ranged from 45° to 60° in steps of 5°. The bridges had a length (L_b in Fig. 59c) going from 15 to 55 mm in steps of 5 mm and a thickness (H_b in Fig. 59c) of 0.4, 0.8, 1.2, and 5 mm.

In their paper investigating aluminum part production by SLM, Calignano et al. [79] proposed a benchmark artifact to evaluate the minimum feasible size of square pins (Fig. 60). The authors tested the part with a pin base size (l) from 0.4 to 0.8 mm, a pin height from 0.8 to 1 mm and a distance (d) between two pins from 0.25 to 0.5 mm.

According to Minetola et al. [73], it is convenient to refer to the ISO standard IT grades [81] when determining the part

Fig. 52 Benchmark artifacts proposed by Jared et al. [62]



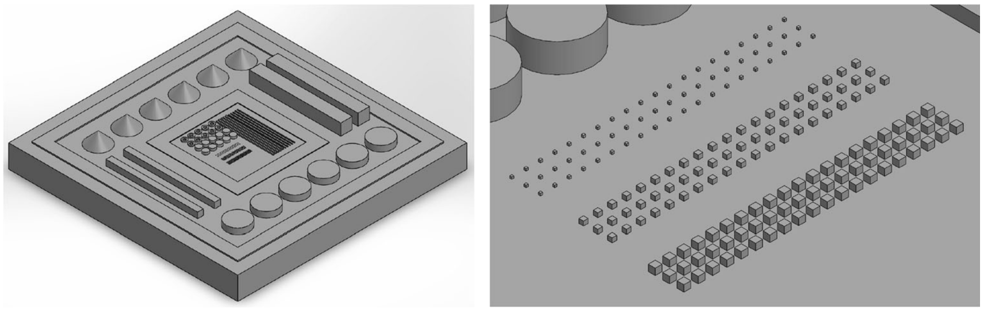


Fig. 53 First design iteration of benchmark artifact by Thompson and Mischkot [68] (*left*: general view, *right*: detail) (overall dimensions = 20 mm × 20 mm × 3 mm)

dimensional accuracy and tolerances in order to facilitate the comparison between different machines and/or processes. However, only a few works on AM benchmarking (for example, [21, 59]) rely on the IT grades and their test artifacts (Figs. 9, 45) have many different features with similar sizes. Minetola et al. proposed a benchmark part (Fig. 61) comprising simple geometries (planes, cylinders, spheres, and cones) in both concave and convex shapes and with different sizes to evaluate tolerances into different ISO ranges.

The benchmark artifact (Fig. 62) proposed by Islam et al. [74, 75] to compare BJ and SL consists of six superimposed concentric cylinders with reducing diameters and a central hole of uniform diameter running through them. This design allows numerous dimensional measurements for each part, thus reducing the number of replicates required for testing.

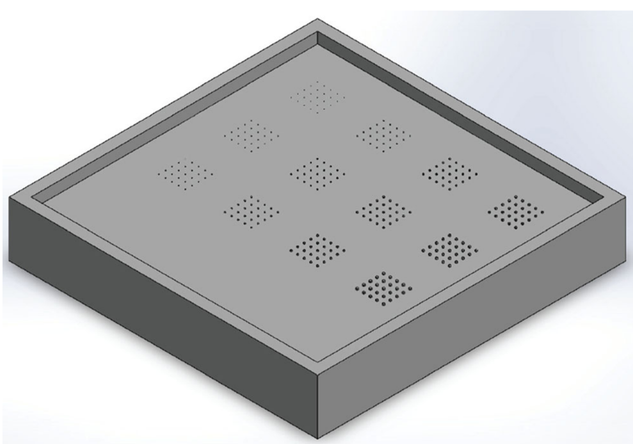


Fig. 54 Second design iteration of benchmark artifact by Thompson and Mischkot [68] (overall dimensions = 14 mm × 14 mm × 2.5 mm)

The study of Berger et al. [77] aims to investigate the accuracy and surface finish of the FDM and SLM processes. The authors chose a modular approach to design their test parts, hence they proposed five separate benchmark artifacts, each one being a different group of varying geometries, distances, and dimensions. The five parts are based, respectively, on the cylindrical geometry (Fig. 63a), the triangular geometry (Fig. 63b), parallel thin walls (Fig. 63c), the dome geometry (Fig. 63d), and the stair geometry (Fig. 63e).

Kniepkamp et al. [78] concentrated on the dimensional accuracy evaluation of micro-SLM when producing small parts with submillimeter features. The benchmark artifact designed by these authors (Fig. 64) is composed by a tube-shaped base plate and four pins, including features like slopes, overhangs, and sharp radii.

2.1 Summary of existing benchmark artifacts

As highlighted by the extensive, although not exhaustive, review presented in the previous section, a wide variety of different benchmark artifacts have been adopted by many authors to assess either the machine or the process capabilities or both. Most of the analyzed test parts include several simple features over a square or rectangular base [2, 7, 11, 12, 17, 19, 24–26, 28–35, 40, 42, 45–47, 49, 52, 53, 55, 57, 59–61, 63–67, 71, 73, 76] (Figs. 5,

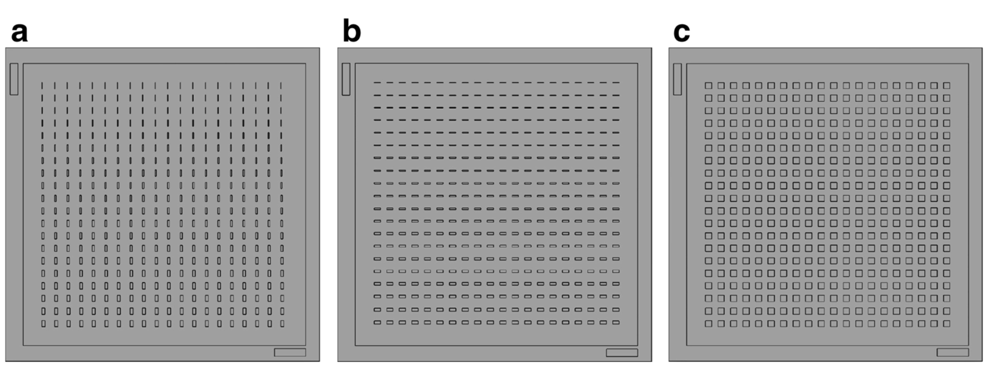


Fig. 55 Third design iteration of benchmark artifact by Thompson and Mischkot [68] (overall dimensions of each part = 10 mm × 10 mm × 5.75 mm)

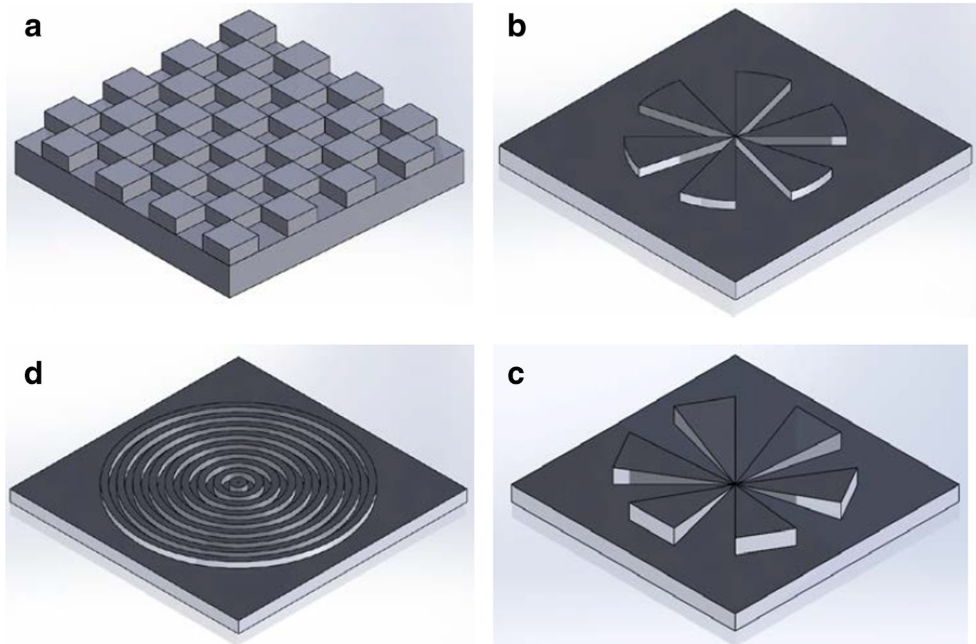


Fig. 56 Benchmark artifacts proposed by Chang et al. [69] (**a** checkerboard, **b** flat ray, **c** slanted ray, and **d** concentric circle)

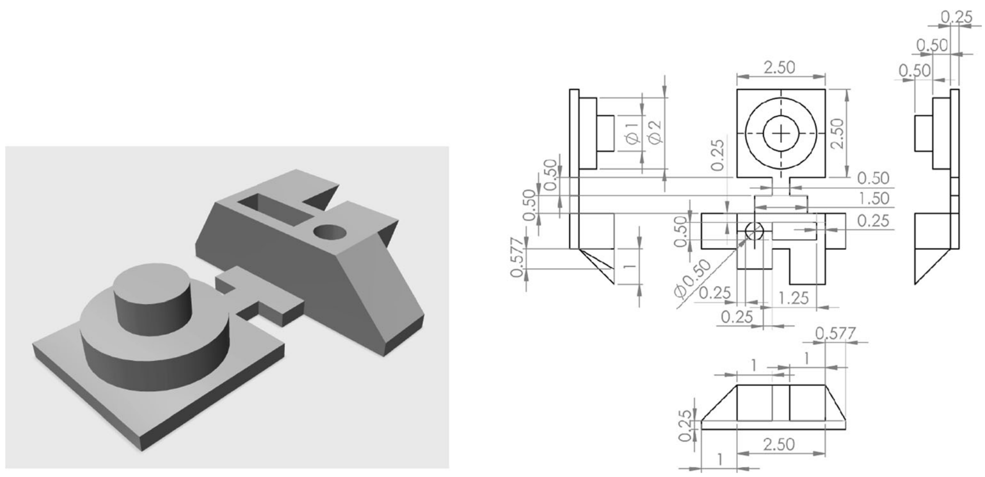


Fig. 57 Benchmark artifact proposed by Decker and Yee [70] (all dimensions are in centimeters)

7, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 25a, 28, 29, 30, 34, 36, 39, 41, 42, 44, 45, 46, 47, 49, 50, and 51, 58, 61). The commonly used features are rectangular/circular holes and bosses, tubes, cones, side notches, and pins. The correspondence between the selected basic features and the assessed geometrical tolerances is described in detail in [2, 28, 32, 42, 52, 53, 55, 76].

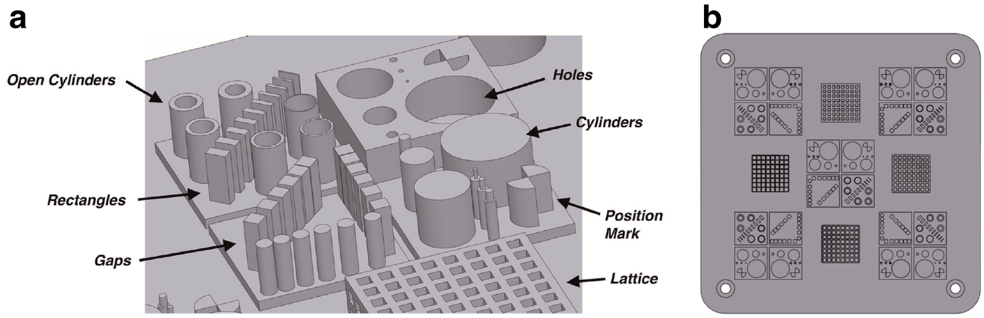


Fig. 58 **a** Benchmark artifact proposed by Teeter et al. [71] (all dimensions are in millimeters). **b** Artifact positions in the building platform

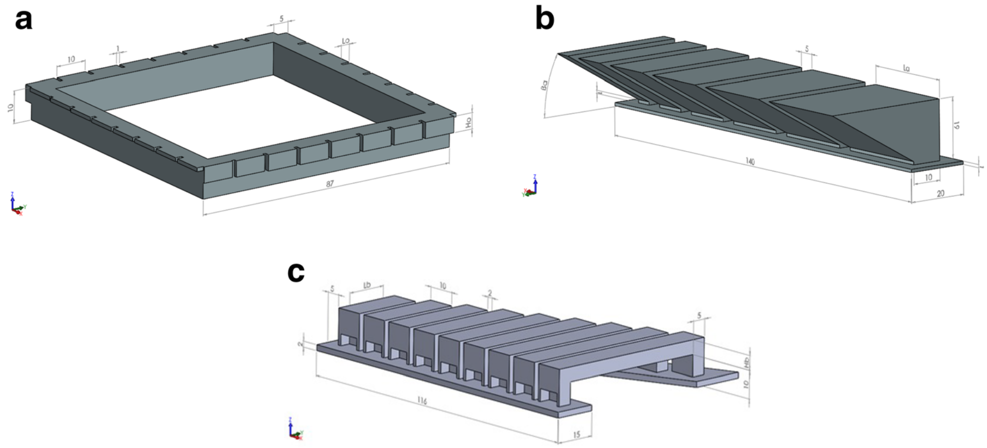


Fig. 59 Benchmark artifacts proposed by Fernandez-Vicente et al. [72]

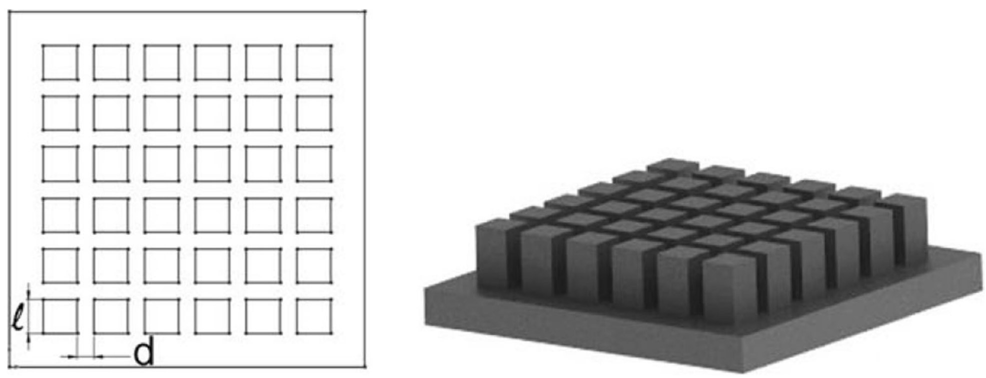


Fig. 60 Benchmark artifact proposed by Calignano et al. [79]

Some designs also include typical features achievable by AM processes, such as overhangs and freeform surfaces [17, 18, 26, 35, 36, 52, 53, 57, 60, 61, 63, 72, 78] (Figs. 5, 6, 14, 18, 21, 22, 23, 39, 50, 51, 59, 64).

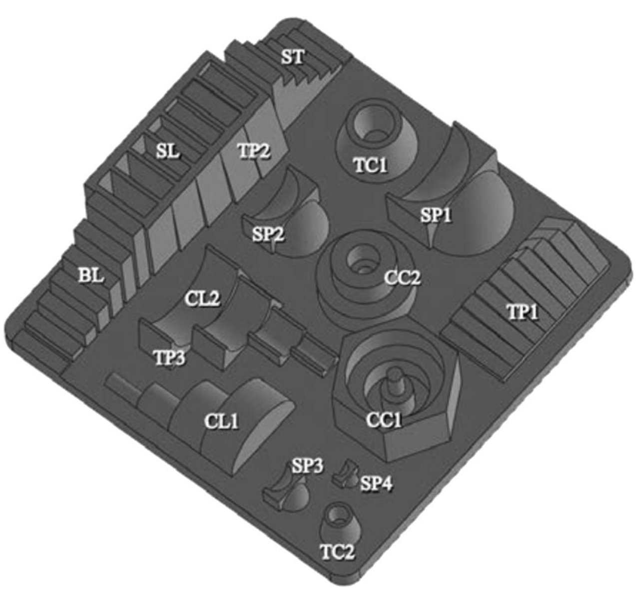


Fig. 61 Benchmark artifact proposed by Minetola et al. [73] (overall dimensions = 110 mm × 110 mm × 33 mm)

Moreover, some benchmark artifacts comprise thin walls and other fine features to investigate the process dimensional limitations [2, 6, 11, 12, 16, 24, 26, 28, 32–35, 38, 41, 45, 46, 49, 52, 53, 57, 60, 61, 63–65, 68, 71, 76, 79] (Figs. 4, 12, 14, 15, 17, 18, 19, 20, 21, 22, 26, 29, 31c, 31d, 36, 39, 44, 46, 47, 50, 51, 53, 54, 55, 58, 60).

A few test parts [6, 13–15, 29, 30, 38] (Fig. 1, 2, 3, 25b, 26, 31b) resemble real objects, thus being less efficient in the

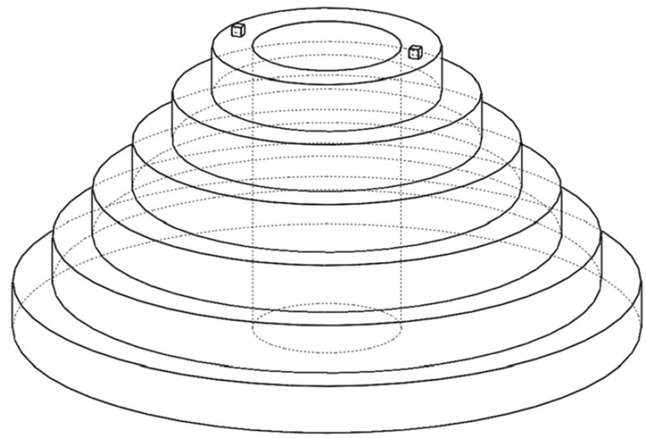


Fig. 62 Benchmark artifact proposed by Islam et al. [74, 75] (base diameter = 126 mm, central hole diameter = 30 mm, total height = 60 mm)

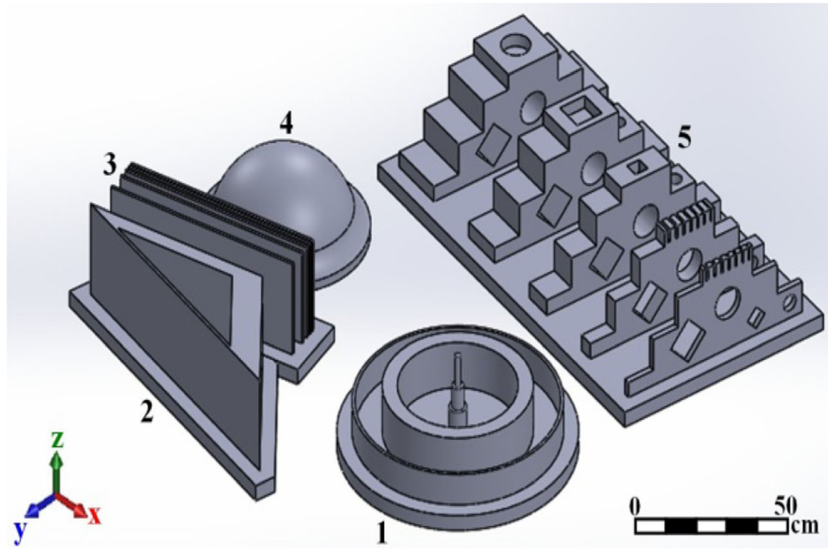


Fig. 63 Benchmark artifacts proposed by Berger et al. [77]

process performance assessment than the artifacts containing simple geometrical features.

It should be noted that three recent studies [60, 68, 78] are focused on the performance evaluation for the emerging micro-additive manufacturing.

The following section critically reviews the main issues in the design of a benchmark intended for the geometrical performance evaluation with the final ambition of drawing a set of design rules.

3 Design of benchmark artifacts for geometrical performance evaluation

The issue of defining guidelines for the design of benchmark artifacts for geometrical performance evaluation has already been addressed by some authors, even if partially. Indeed, they refer to specific machines/processes or they focus only on some aspects.

For example, Jacobs [82] defined some rules considering the stereolithographic process. He stated that the ideal test part should include a substantial number of small, medium, and large common features (e.g., cubes, thin walls, and cylinders) and that these features should be both positive (i.e., protruding above the base surface) and negative (i.e., expanding below the base surface). Moreover, Jacobs claimed that a benchmark artifact should be large enough to test the system performance both at the building platform center and at its edge, but, at the same time, it should not require an excessive amount of material and not take too long time to build. Eventually, Jacobs highlighted that a suitable test part should be easily and quickly measurable. Following their study, Byun and Lee [28] added that a benchmark artifact should include features aligned along all axes and include features to assess the minimum feasible size of fine geometries. Scaravetti et al. [42] focused their research on determining the sources of the measured defects, hence they just stated that a proper test part should include simple geometrical shapes, require no post-treatments, or manual interventions (for this reason, e.g., there should be no support structures) and allow the assessment of spatial repeatability.

This section takes into account all the aspects of the geometrical performance evaluation and presents a comprehensive discussion on the non process-specific guidelines for designing the benchmark artifacts.

3.1 Guidelines to design benchmark artifacts for geometrical performance evaluation

The very first benchmark artifacts used for AM accuracy evaluation have been designed based on real objects and their usefulness was limited. Indeed, these test parts contained only a few features whose accuracy was interesting for the

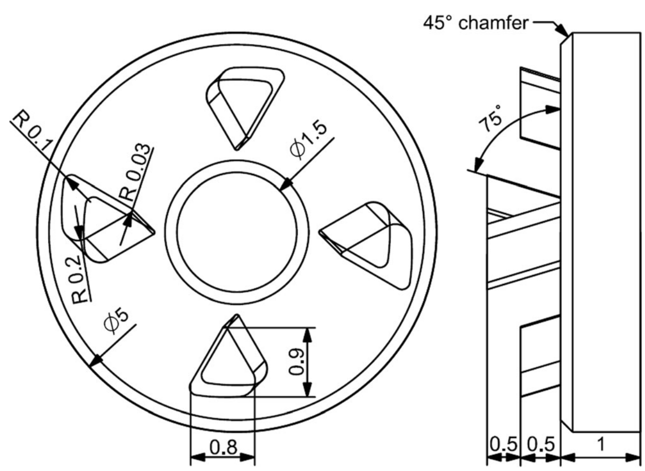


Fig. 64 Benchmark artifact proposed by Kniepkamp et al. [78] (all dimensions are in millimeters)

Table 2 Examples of simple features used to evaluate the main geometrical tolerances

Geometrical tolerance	Features
Flatness	Cubes, slots, rectangular bosses, thin walls, base surface of the test part
Straightness	Cubes, slots, rectangular bosses, thin walls, base surface of the test part
Circularity	Circular holes, cylinders
Parallelism	Cubes, rectangular bosses and holes, thin walls, square holes
Perpendicularity	Cubes, circular bosses and holes, square holes
Cylindricity	Circular holes, solid and hollow cylinders
Angularity	Inclined surfaces
Position	Holes, cylinders
Profile	Spheres, hemispheres

producing companies and, moreover, they have not been developed taking into account the specific characteristics and critical issues of AM processes.

Most of the later benchmark artifacts included several basic features over a square or rectangular base, being specifically designed to evaluate the performance of AM technologies in terms of dimensional or geometrical accuracy, repeatability, and feature minimum size. The analysis of such test parts allows to highlight their fundamental characteristics and, although it is impossible to design a universal benchmark artifact, it is possible to draw some non-process-specific design guidelines. The following subsections summarize these design guidelines in four categories: overall test part dimensions, feature geometry, feature dimensions, and feature position and orientation. Based on these guidelines, a suitable benchmark artifact can be designed to evaluate the process aspects of interest, selected among dimensional accuracy, geometrical tolerances, repeatability, and minimum feature size.

3.1.1 Overall dimensions

The benchmark artifact should allow to evaluate the accuracy of the system/process within the whole building platform of the machine, hence its base plate should has the same size as the platform or, if it is smaller, it should be replicated at the platform corners and center. This assessment is important in order to take into account potential axis errors due to backlashes or a poor assembly quality (this is typically the case of self-assembled FDM machines) or due to non-uniform machine performances (e.g., in the case of non-Cartesian architectures).

It has to be noted that a large base surface increases the risk of part warping, which could lead to problems in the measurement process and, consequently, to a lack of result robustness. However, the warping phenomenon could be avoided adopting a specific part design. On the other hand, a small base surface could prevent from placing all the necessary features (Section 3.1.2), with a wide dimension range (Section 3.1.3), in a suitable position and at a proper distance (Section 3.1.4).

Moreover, the total part volume should not be excessive in order to limit the material consumption and the manufacturing time.

3.1.2 Feature geometry

Both convex and concave, flat and non-flat, simple geometrical features that do not require support structures (e.g., cubes, rectangular bosses and slots, cylinders, thin walls, and circular holes) should be included in the test part in order to evaluate several dimensional accuracy and geometrical tolerances (e.g., straightness, flatness, parallelism, cylindiricity, roundness, concentricity, and perpendicularity). For the sake of brevity, a complete correspondence between all tolerances and basic features cannot be reported here, but Table 2 report some examples of features that can be used to assess the main geometrical tolerances.

Given the desired tolerances to assess, redundant features should be avoided since they imply a waste of measurement time.

More complex features, such as overhangs, inclined surfaces, bridges, and freeform surfaces, are used to test the process limitations with regard to specific AM geometries, but they can be difficult to measure.

3.1.3 Feature dimensions

The test part should have features in a wide range of dimensions, in order to assess the process performances with respect to different magnitude orders. The lowest limit of the feature size is set by two factors: the positioning precision of the AM machine axes and the resolution/limitations of the selected measurement system.

Small geometries with a regular dimension increment allow to evaluate the minimum feasible feature size.

3.1.4 Feature position and orientation

The features should be aligned along all the machine cartesian axes to evaluate the geometrical/dimensional along the x, y, or z directions. At the same time, the features should be positioned as to allow and facilitate the measurement process, considering the selected measuring system.

If the research aims to evaluate the system spatial repeatability, repeated features at different locations are needed in case of a large test part; otherwise, the benchmark artifact should be replicated throughout the machine building platform.

3.2 Measurement issues in benchmark artifacts

The measurability of the benchmark artifact is a key issue and it represents a tight constraint in the design process. Indeed, the test part has to be designed taking into account the selected measurement system, since the features that cannot be measured are useless and result in a waste of time and material.

As mentioned in Sections 3.1.2–3.1.4, the resolution and limitations of the selected measurement system have a direct influence on the geometry, minimum size, position, and distance of the artifact features. For example, considering a CMM, the stylus tip radius determines the minimum dimensions of measurable features while the accessibility of deep features is related to the stylus length. When using an optical measurement system, e.g., a focus variation microscope, some steep surfaces or undercuts could not be completely acquired. For this reason, before designing the test part, it is fundamental to define not only the dimensional/geometrical performance to assess but also the measurement system that will be used.

4 Conclusions

This paper has proposed an extensive review of the available literature on the so-called "geometrical benchmarks" that are used for evaluating the performance of AM processes in terms of dimensional or geometrical accuracy, repeatability, and feature minimum size.

These artifacts can also be exploited to compare different AM systems relying on the same technology or different AM technologies, if the results of the geometrical/dimensional performance assessment are combined with other parameters, such as surface roughness, mechanical properties, manufacturing time, and costs (see [18, 31, 34] for some examples of comparison).

As mentioned in Section 1, benchmark artifacts for geometrical performance evaluation can be also used for the parameter optimization of a specific AM system, since some features are specifically related to a certain process. Some examples of process optimization based on such test parts can be found in [25, 40] (SL), [33] (SLS), [36, 47, 54, 59, 66, 67] (FDM), [64, 65] (MJ).

Thanks to the analysis of the existing test parts, the paper has drawn and discussed some non-process-specific guidelines to design benchmark artifacts for geometrical performance evaluation. Based on these guidelines, a suitable benchmark artifact can be designed to evaluate the performance indicators of interest.

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