CEN WORKSHOP AGREEMENT

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Methods for the process control of high-resolution mono- and multimaterial additive manufacturing

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European foreword

This CEN Workshop Agreement (CWA 18132:2024) has been developed in accordance with the CEN-CENELEC Guide 29 “CEN/CENELEC Workshop Agreements – A rapid prototyping to standardization” and with the relevant provisions of CEN/CENELEC Internal Regulations — Part 2. It was approved by a Workshop of representatives of interested parties on 2024-05-31, the constitution of which was supported by CEN following the public call for participation made on 2023-10-30. However, this CEN Workshop Agreement does not necessarily include all relevant stakeholders.

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Introduction

Additive manufacturing (AM) is a rapidly advancing field of technology with new boundaries being constantly widened. From the original 3D-printing of monomaterials, AM has advanced to increasingly complex multimaterial printing with a new dimension of printing resolution. This poses a challenge to existing quality control strategies, with novel expectations towards accuracy and new aspects regarding material behavior. Multimaterial interactions and the developing field of 4D-printing pose completely new tasks for planning, executing and analyzing conclusive quality control processes for AM.

This document aims to establish a conceptual framework of a standardized procedure to establish a quality control covering the entire production cycle from design to finishing. As it is building on experience during the EU Horizon 2020 INKplant R&I project (funded under grant agreement number 953134), a special focus is made on ceramic lithography and inkjet multimaterial printing, but the concepts are to be implemented with the purpose of generalization.

The areas covered attain an increased significance in the context of medical implants, especially as AM manufactured implants for tissue engineering are generally applied in high risk classes.

1 Scope

This document describes a framework for

- the evaluation of additive manufacturing (AM) systems capability and performance boundaries,
- the installation calibration of AM systems and
- risk assessment and evaluation for medical AM.

It defines accuracy and resolution in additive manufacturing and their special meaning for multimaterial prints as well as 4D-prints, consequences for design, with steps towards a standard for implementing a general measure of these parameters. Alignment and boundary behavior of multimaterial AM are related aspects.

There is a section on design, where multimaterial boundaries can influence mechanical behavior.

The procedures of accuracy determination are then applied to evaluate the influence of positioning in the build room and orientation of the printed object. Very often, the stratified nature of AM procedures leads to an influence of orientation on surface finish and stability. When high-resolution surface patterns are printed, this aspect becomes more important.

Entrapment of raw materials (inks, powders, resins) gains a new dimension for multimaterial prints. The removal of support structures is therefore also regarded in this context.

Standardized control of the aging of raw materials using in-process control is another concern.

Finally, there are always remaining steps that have to be executed by manual labor and are therefore dependent on skill and practice level of an individual. In this document, a framework for accessing process control of these often critical process steps is proposed.

2 Normative references

There are no normative references in this document.

3 Accuracy determination

Accuracy is a central criterium to consider during design, layout, material selection and post-processing, making it necessary to determine the target accuracy as an initial step.

3.1 Accuracy definition

Accuracy has several aspects, it can refer to the ***resolution*** of the smallest printable structure (accuracy of representation of an infinitely resolved detail) or the match between the required and the actually realized structure (***process accuracy***). Both are covered within this document.

In AM, each accuracy has at least the dimensions x, y and z, with most current methods having equal accuracy in x and y and different one in z direction, and additionally t as the time. For printers with more axis, additional accuracy dimension e.g. 4th and 5th axis may be added. A numeration scheme of a, b, etc. is suggested for these further “dimensions”, alternatively Greek letters can be used. It has to be remembered that these dimensions only exist in respect to the accuracy of the printer mechanics, they are not found when analyzing the part alone. In those cases, process accuracy and physical accuracy of the part shall be regarded separately.

3.1.1 Resolution

Ra: Smallest realizable voxel as defined by machine parameters, e.g. stepper motor steps, laser beam width, light source pixel

Rr: Smallest realizable structure

Rm(2…n): Smallest realizable dimension of n multiple materials printed together

3.1.2 Process Accuracy

Ad: distance match, the percentage of concordance with theoretical for a distance measured between two measuring landmarks

At: tip match, the percentage of concordance between a printed acute structure and the template, suggested as area fraction

Ar: ratio match, the deviance from the ratio 1 between two distances of an equidistant geometrical structure, e.g. of a cube or sphere

Aa: angular match, the percentage of concordance between an angle formed by structures in two geometrical dimensions and the template, equals skewedness

Am(2…n): multimaterial contact accuracy, the size of the gap at the boundary of n materials that were designed to have direct contact; negative values describe a “mixing zone”, the distance to the templated boundary that neighbouring materials have mixed

Ai(2…n): interference accuracy: the percentage to which a geometrical accuracy is changed by neighbouring materials as compared to single materials, e.g. by differently shrinking materials that act on each other; it can be given both for the distance that an effect is observed (e.g. an infiltration or colour change) and the magnitude of a change (e.g. distance of retraction from the interface)

3.2 Accuracy determination

In order to measure the different accuracies, standard reference structures are needed. A library of standard reference structures suited for high resolution, multimaterial and multidimensional comparison is given in CWA 18130:2024, *Standardized scaffolds library for tissue engineering research and industrial applications*. This description references to the library. Additional structures are provided together with this document.

3.2.1 Resolution

While Ra is commonly determined by the machine manufacturer during IQ/PQ processes and given, the Rr depends on the material properties. It can be determined by using the geometric surface patterns and scaling them in several steps. Usually, the smallest possible detail is not below 3x Ra.

By scaling objects from the multimaterial scaffold library, Rm can be determined. As the library is set out for 2 materials, for Rm(n>2), some voxels shall be substituted by the added materials.

An alternative is to use fractals for the determination of maximum accuracy. A Koch-curve, from 1st iteration onward, a Sierpinsky triangle/pyramic, Sierpinsky carpert/Menger sponge or a Lévy-C-Curve are suitable reference designs, the latter especially for shape-changing 4D-prints. In this case, the structures shall be realized with sufficiently high detail (sufficient iterations) with a base length of 1cm for the iteration 0 and sent to the printer. Afterwards Rr can be determined as the highest iteration still represented in the printed structure. A Koch-curve-based 3D-Object is provided with this document.

The test structure can be scaled to meet the dimension of the respective technology, for example by using 1m as base length for large object printing or 1 µm for nano-scale additive manufacturing processes.

To report the result of the accuracy measurements, the test structure shall be listed as named in Annex 1, then the scaling factor is given and for fractals, the highest realizable iteration, e.g. for the 3D-Koch-type object scaled to 10cm KFrac-10/5 = S ± V; in this case a 10x magnified base object of type Kfrac, shall be realized to 5 iterations; S is the systematic deviation or difference of mean from theoretical length of the smallest side and V is the variance of measurements.

The geometrical accuracies can be evaluated in the time dimension t. Ra(t) does not exist.

Rr(t) shall be calculated from Rr(x,y,z) by repeating the measurement after time-dependent processes have taken place. These can be shrinkage, drying, debindering and sintering, or folding of metamaterials during 4D-printing processes.

For shrinking geometries, e.g. ceramic prints, the resulting achievable accuracy is a product of smallest printing accuracy (t=0) and shrinkage.

Rm(t) shall be derived accordingly.

For 4D-printing, changes in dimension shall be adapted to the shape-changing processes, which require an additional time-dependent evaluation of geometrical variables, giving an additional result. Imprinted patterns within the folded structures can be analyzed for the classical Rr(t) and Rm(t) parameters.

It is important to notice that the influence of the highest possible process resolution Ra results in discrete steps of resolution, since only the Ra steps of accuracy can be realized. Intermediate dimensions are either reduced or enhanced.

The final attainable resolution Rr/Rm is Ra x minimum necessary steps x shrinkage.

Example: At 40 µm resolution in x and y direction, a 100 µm structure will either be printed as 80 µm or 120 µm. The final realizable dimension is this Ra value x shrinkage. At a sinter shrinkage of 20%, the resulting detail will be 64 µm or 96 µm, respectively. When a minimum of 2 voxels can be realized technically, Rr(x,y,t) = 32 µm x Z with Z=2,3,… as natural number.

3.2.2 Process accuracy

To determine the match of a given structure, geometrical test objects defined in this document shall be used. These are cubes, isometric spheres, tetrahedrons and a flower-petal structure. They should be adjusted to 100 x Ra.

Evaluation is described in Annex I.

Precision measurements should be made during IQ for all positions in the build room, during production single reference structures can be sufficient for process control. This section does not include object placement in the build room, which has its own section.

Cubes: used for distance measurement for x, y, z and in repetition for t, as smallest distance of parallel sides. References to existing standards of measurement are required. Also used for determining the ratio of side lengths, and angular match for 90 °C

Ad, Ar, Aa, At

Isometric Spheres: used for relation measurement between geometrical axis x, y, z, over t. Deviation from the perfect arc is a measure of ratios in x, y, z.

Ar, (Ad)

Tetrahedrons: The point of the triangles can be used for measurement tip match, by determining either the distance of the actual tip from the theoretical meeting point of the prolonged sides, or the area of a perfect triangle not covered. The cross-section gives a square for measurements similar to the cube base sides. The deviance from 60 °C gives the angular match and can also be used as a measure for skewedness.

At, Aa

Petal structures: The acute tip of a standardized petal is another method to measure acuteness, either as distance of the realized tip to the expected tip, following the structure outlines, or as percent area covered.

At

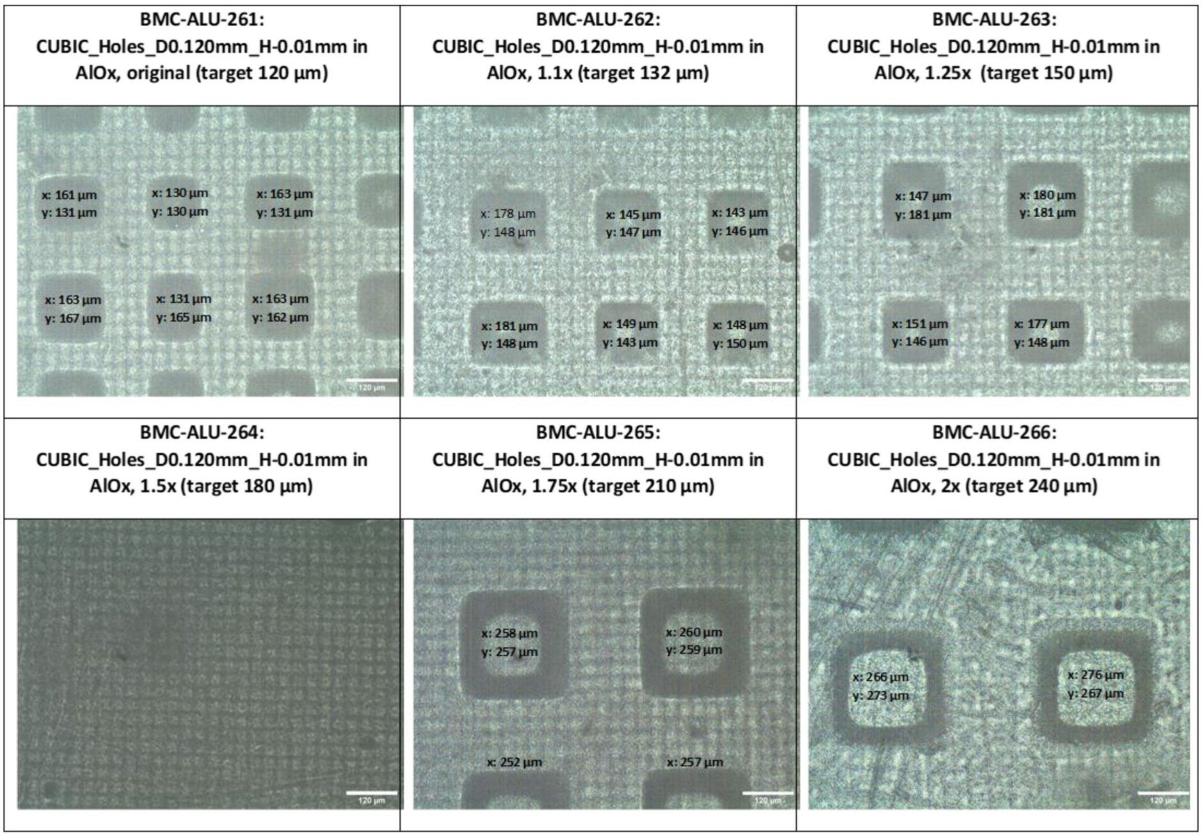
Models from the standard library (CWA 18130:2024) are recommended for the determination of Am and Ai.

4 Design

4.1 Design and accuracy

When preparing a file for design, the maximum possible resolution, as calculated in 2.2.1, shall be considered. The closer the highest detail or smallest deviation in size to be realized comes to Ra(t) (after shrinkage), the more important it is to align the design to the additive manufacturing grid or resolution (e.g. pixel-align function for printers).

Using scaled patterns from the standard library, interference effects of the design with the printing resolution can be tested [for an example, see Figure 1].



BMC-ALU-261: CUBIC_Holes_D0.120mm_H-0.01mm in AlOx, original (target 120 µm)

BMC-ALU-262: CUBIC_Holes_D0.120mm_H-0.01mm in AlOx, 1.1x (target 132 µm)

BMC-ALU-263: CUBIC_Holes_D0.120mm_H-0.01mm in AlOx, 1.25x (target 150 µm)

BMC-ALU-264: CUBIC_Holes_D0.120mm_H-0.01mm in AlOx, 1.5x (target 180 µm)

BMC-ALU-265: CUBIC_Holes_D0.120mm_H-0.01mm in AlOx, 1.75x (target 210 µm)

BMC-ALU-266: CUBIC_Holes_D0.120mm_H-0.01mm in AlOx, 2x (target 240 µm)

Figure 1 — Results of a lithographic print (CeraFab 7500, Lithoz) with Aluminiumoxide-Slurry of the standard library pattern CUBIC_Holes_D0.120mm_H-0.01mm (see CWA 18130), scaled to different dimensions; target patterns are regular squares/cubes, the target edge length is given above each result. The small grid represents the Ra resolution of the printer, 40 µm x 40 µm, in xy-direction. Interference of the design with the resolution has resulted in different sized rectangles, more significantly for smaller structures

Distances between relevant structures should be multiples of Ra in the design that is sent to the printing process. If shrinkage compensation is automatically applied, this shall be considered during design.

When the object has to fit into a gap or other part, the process accuracy according to 2.2.2 shall be considered. If non-match is a high risk, the dimension shall be designed to result in a smaller/larger structure to accommodate for the inaccuracy parameter.

For mechanical stability, points of stress shall be considered in a different way for multimaterial processes [see Figure 2 for an illustration]. Thus, lateral stresses meeting a material A with different mechanical properties first with an interface to B will lead to a different overall behavior then when meeting B first. On critical points and sites of stress, material selection in multimaterial designs is crucial and shall consider not only actual resilience but also crack propagation.

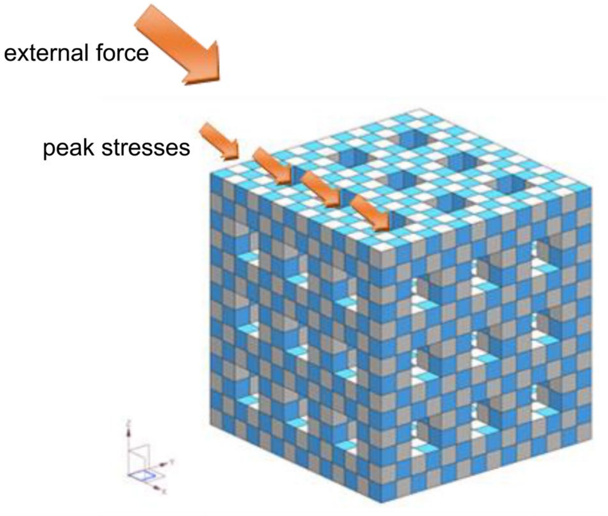


Figure 2 — In multimaterial compositions, as in this example from the standard library (see CWA 18130:2024), the material allocation at critical stress points can determine overall stability. In this illustration, a diagonal force would place a different stress on corners. Selecting a more resistant material for the blue volumes will results in better resistance, but for stresses from the opposite direction, the contrary is the case

Quality control of design processes shall be realized by comparing design intent for critical sections with the results from accuracy measurement of printed parts.

4.2 Design and multimaterial printing

Material interactions shall be considered during design.

In order to produce a valid printable structure, the constraints and course of the multimaterial printing process shall be taken into account, including but not limited to deposition order, curing, solvents, time-dependent processes and after-treatment like removal of support structures.

Results from the determination of Rm, Am and Ai are crucial for the design process.

4.3 Design and build-room positioning

Results from object orientation analysis shall be taken into account and correlated with possible build-room positioning. When deciding on which structures can be realized, removal of excess material and support structures shall be taken into consideration. Different to CAD-CAM processes, AM processes often require considering the resulting layer structure, which can change geometries, alter surface patterns and influence stability. Before starting the process, the relation of maximum accuracy for each dimension to the overall geometry shall be regarded and the layer orientation optimized to withstand main mechanical forces. Making differently tilted or rounded surfaces can be used during design to encounter this effect.

Both multimaterial and build-room positioning shall be controlled by evaluating the resulting object.

5 Build-room position and orientation

A cube and a sphere shall be positioned side-by-side at different positions, covering the entire build-room. For multimaterial processes, only a cube can be used, taken from the standard library for multimaterial scaffolds (CWA 18130:2024).

For orientation validation, a cube shall be oriented with one side in each plane xy, xz and yz and the other sides at 45° angle to the remaining planes, as shown in Figure 3.

Evaluation shall be done by dimensional measurements of distances, tips, angles and proportions as for Ad, At, Ar and Aa. Values are calculated as percent deviation from ideal geometries in reference to the given factor. Time dependence can be added. Cubes can be modified with surface patterns to test orientation influence on pattern realization.

For multimaterial prints, Am and Ai shall be additionally defined. For 4D-prints, a flat petal structure shall be printed in xy-plane, xz plane and at 45° angle to the xz-plane and degree of folding analyzed and given as relative value to the xy-plane. If isometric change occurs, a flat triangle or tetrahedron shall be printed in the same orientations and side lengths, angles and volume shall be measured and given as percentage of the print with the base in xy-plane.

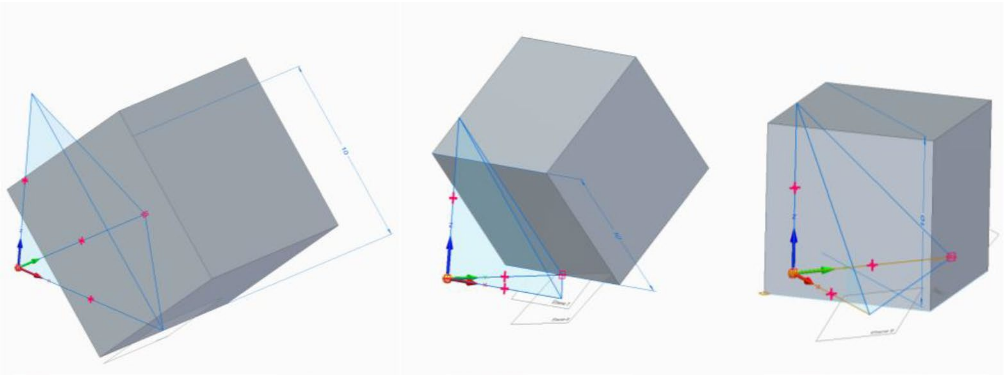


Figure 3 — The 3 cubes for testing build room positioning, from left to right: Positiontest_01_xz, Positiontest_02_yz and Positiontest_03_xy

6 Printing process

6.1 Printer position accuracy

Using coloured inks and a fixed starting position on the printing bed, positioning accuracy shall be tested for the entire range of feasible printing speeds. Movement processes are subject to inertia and speed can influence the accuracy, since position is usually referenced once to a zero-point at the start. Inaccuracies can result from too high speed at high load (e.g. heavy print heads), from worn or slipping transport belts or play in the transport spirals. **It is important that the required positioning accuracy is not smaller than Ra; otherwise the entire design process shall be revised**.

For the test, the images in Figure 4 can be used. In order to include z-position, cubes can be added, then ideally stacked accordingly in z-direction.

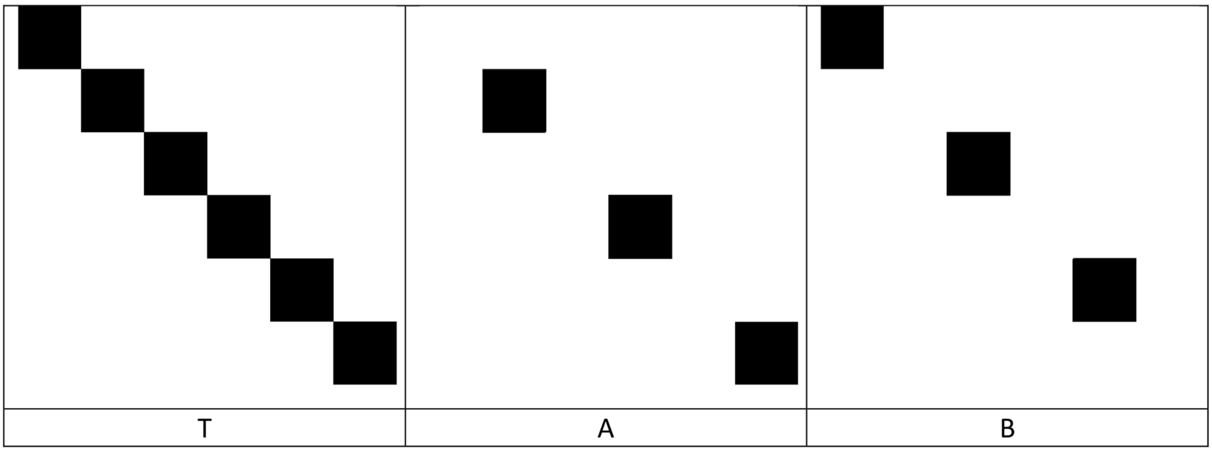


Figure 4— Test geometries for printer positioning accuracy measurements. T = total figure, A and B printed on top of each other should result in T

The qualification process shall include:

- The image T is printed three times and the distance from the starting line to the first line of each square is measured, as well as the side lengths for each square. If it is difficult to determine the starting point, the figure can be printed three time on top of each other, providing the prints can be told apart afterwards. For some procedures, z-stacking the prints is a solution.
- Image A is printed first, then image B on top. The same parameters are measured and the matching of the square sides for A and B compared to T.
- For multimaterial systems, A and B are then printed with pairs of different materials. Each material extrusion system (e.g. printhead) should be examined separately.

6.2 Material quality

Many references to standards for material quality control can be given.

Here, the following additions shall be made:

- For materials hardened by a light source, the time under standardized light intensity for viscosity, measured as resistance to a rotating cone-on-plate, to decrease to 50% is controlled as a parameter of quality.
- Weight loss upon heat treatment can be a solid quality parameter for solvent-containing systems (decrease with time) and powders (increase with time).
- Solid content and sedimentation speed are important for inks that contain dispersed particles.
- When cleaning fluids are used, gradual dilution of the stock with these is an important quality parameter.
- In multimaterial systems, contamination of raw materials by the other materials should be quantified, especially at the printing interface; this includes mist or backsplash.
- For multiple extrusion system (like inkjet printheads), the number of clogged nozzles shall be controlled and functional limits specified.

6.3 Post processing

After the print, several parameters shall be controlled.

Control of process parameters linked to automated systems can be performed during IQ/PQ.

Human interaction shall be controlled by a defined training system, using sufficiently large series of parts, and should be additionally controlled by standard part controls at different times (for examples after different work hours, weekdays, weather conditions, seasons) to record the range of variation and encourage a sensitivity towards homogenous results. A comparison and, if possible, approximation of results between different trained persons should be realized at regular intervals.

6.3.1 Time to removal of the part

There is a minimum time e.g. for draining of fluids or hardening of parts, and a maximum time, e.g. for surplus growth of parts through continued solidification or binding of powder.

The optimal time shall be determined, apart from mechanical stability on removal, by serial qualification measurement with objects in the entire range of sizes that are to be printed, and including the entire range of complexities in designs, for example of pores. Dimensional measurements and weight after cleaning are the parameters of choice.

6.3.2 Slurry/Powder removal

Slurry or powder removal can be either done by automated systems, which can be adjusted to optimal values, or trained staff, concerning the training for human interaction.

The analysis should be conducted by both weight of standard test structures, optimally representative build parts, and dimensional verification using landmarks.

6.3.3 Support structure removal, removal from carrier plate

Removing support structures or removing the part from the carrier plate is usually a human interaction and should be qualified as described above.

Additional to weight and dimensional measurements, crack occurrence and mechanical stability can be suitable control points.

For both slurry/powder and support structure removal, the relation of components is an important measurement for multimaterial systems. This can either be evaluated by removing one material after the other and weighing the difference or by comparing the overall density for materials with different densities, providing that the content of at least one part can be considered as fixed, and the change in quantity of the determined components is measurable at reasonable rates.

Annex A
(normative)

Test structures with standard dimensions and analysis methods

A.1 Test structures from the Standardized Scaffolds Library

The geometries given by CWA 18130:2024, *Standardized scaffolds library for tissue engineering research and industrial applications,* are referenced here.

For surface pattern: https://zenodo.org/records/6387580

For 3D-structures: https://zenodo.org/records/6387574

A.2 Test structures for Resolution

A.2.1 Monomaterial Resolution Rr

To test for highest possible resolution and accuracy, surface pattern structures shall be used. The recommended geometry is “**TestTube_D_e100_ab100 (D4)**” from the “**OS_Textured_Probes_Collection**”.

An alternative pattern can be used, but a written justification, describing how the structure can be compared to results using the recommended structure has to be given.

To apply the geometry, follow the following steps:

a) Determine Ra as described in “2.2.1 Resolution“.

b) The geometry is given with 100µm edge length per cube. Using a software for modifying .stl-files, scale the geometry to 3 x Ra per edge length. This is the highest achievable resolution. Make sure the software does not prevent accurate representation of the resulting structure. Alternatively, the target structure can be produced accordingly using a CAD software.

c) Reproduce the structure generated in b) by scaling:

2.5x, 10x, 25x, 200x, 500x, 750x, 1000x

d) Print at least 4 versions of each resulting model using your standard established printing pathway with the parts placed such that the edges of the squares are aligned in x and y direction, respectively, with the elevation aligned in z-direction. Structures can be printed either together with one copy of each size in 4 batches or as distributed 4 samples per batch.

e) For evaluation, measure the edge length of at least 10 squares per sample in x, y and z direction (Figure A1). For larger models, where less then 10 squares might be realized per sample, these can be pooled over all 4 samples. Depending on dimensions, use either a light microscope, scanning electron microscope or manual measuring device to evaluate edge length. When using digital imaging, make sure systems are calibrated and perspectives are not distorted in viewing direction of the dimension measured.

f) Calculate the mean relative deviation from theoretical edge length for x,y and z direction.

g) Rr is defined as the smallest edge length that can be realized with less than a given percentage of deviation. The relative deviation shall be given together with Rr, for example as

   Rr(10%) = 120µm

   Standard deviations of 10%, 5% and 1% are recommended here, but the level of accuracy shall be defined by the application constraints.

Rr (x%) is given specific to a material, printer, printing conditions and process step, e.g. before/after sintering, storage, sterilization or other.

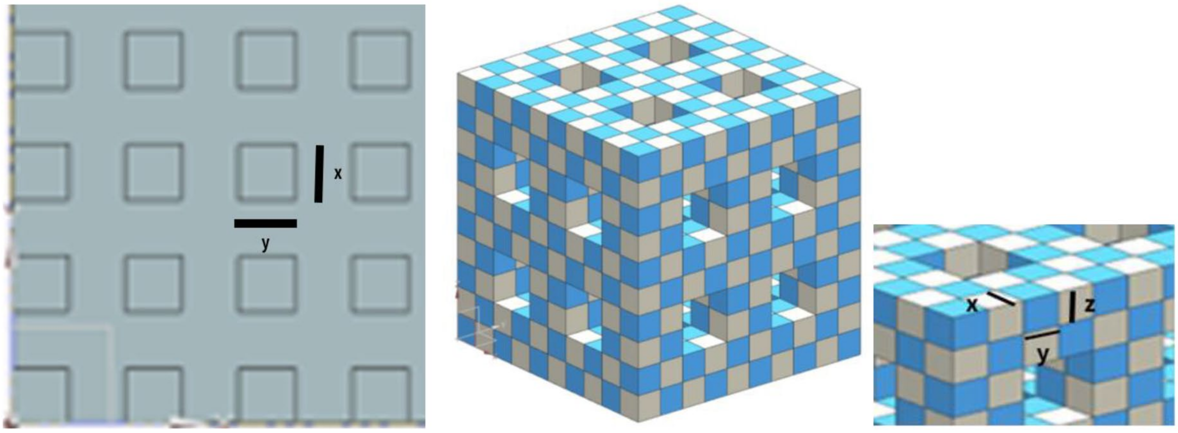


Figure A.1 — Left: Measurement of dimensions for TestTube_D scaled structures; z the cubic pillars are shown in top view, represented by squares, z is measured as height of the cubes from the interspace level. Right: Dimension determination for 500 micron element 5x5x5mm_D500; each material is measured with at least 10 cubes separately

A.2.2 Multimaterial Resolution Rm(n)

To test for highest possible resolution and accuracy for scaffolds composed of multiple materials, one of the files in OS_Scaffolds_Library_Multimat\J_MULTIMATERIAL_MULTISCALE_DIGITAL_MATERIALS\3D is recommended.

The recommended geometry for 2 materials is a combination of “**3D_Element_D500_MatA.stl**” and “**3D_Element_D500_MatB.stl**”.

Other structures from this library can be used. A short explanation justifying the choice of the structure should be given in the evaluation report.

To apply the geometry, follow the following steps, exemplary for 2 materials. For more materials, further cubes shall be inserted into the structure.

a) Determine Ra as described in “2.2.1 Resolution“.

b) Using a software for modifying .stl-files, scale the geometry to 3 x Ra per edge length in x,y and z direction of the cubes, processing both stl files equally. This is the highest achievable resolution. Make sure the software does not prevent accurate representation of the resulting structure. Alternatively, the target structure can be produced accordingly using a CAD software.

c) Reproduce the structure generated in b) by scaling:

 2.5x, 10x, 25x, 100x

d) Print at least 4 versions of each resulting model using your standard established printing pathway with the parts placed such that the edges of the cubes are aligned in x, y and z direction, respectively. Apply appropriate support structures, if necessary. Structures can be printed either together with one copy of each size in 4 batches or as distributed 4 samples per batch.

e) For evaluation, measure the edge length of at least 10 cubes per material per sample in x, y and z direction (Figure A.1).

 Depending on dimensions, use either a light microscope, scanning electron microscope or manual measuring device to evaluate edge length. When using digital imaging, make sure systems are calibrated and perspectives are not distorted in viewing direction of the dimension measured.

f) Calculate the mean relative deviation from theoretical edge length for x,y and z direction.

g) Rm is defined as the smallest edge length that can be realized with less than a given percentage of deviation. The relative deviation shall be given together with Rm, for example as

 Rm(2, 10%) = 120 µm

 Standard deviations of 10%, 5% and 1% are recommended here, but the level of accuracy shall be defined by the application constraints.

Rm(n,x%) is given specific to a material, printer, printing conditions and process step, e.g. before/after sintering, storage, sterilization or other, with n representing the number of materials used together in the test.

A.2.3 Monomaterial Resolution Rr using Fractals

The recommended geometries are “**KFrac01_11.stl**” and “**KFrac01_11-half.stl**”.

The choice of model, scaling and number of iteration steps should be reported and explained together with the evaluation results.

A 3-dimensional reconstruction of a Koch-Flake like fractal is provided with this document. The construction is made using a CAD software as follows:

A regular tetrahedron with 10mm edge length is constructed. For example, in SolidEdge Software, the base is extruded to more than the edge length, than the “draft” tool is used to tilt the three new sides at an angle of 19,471, which is the tetrahedron angle minus 90°. Alternatively, the Euklidean method can be used.

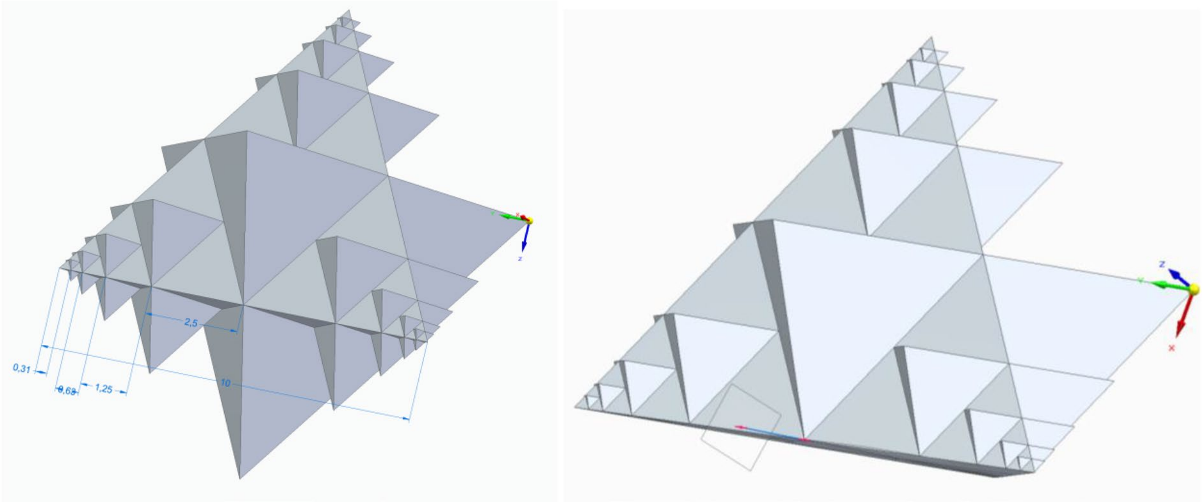


Figure A.2 — KFrac01-6, a 3D-Fractal constructed as using the Koch-Flake algorithm for the division of one side of a tetrahedron. This results in a printable object with increasingly smaller detail. Distance inaccuracies result from distance accuracy presets in SolidEdge, the CAD software used. On the right hand side a truncated version is shown with all details removed on the bottom side, enabling printing in system requiring attachment to the flow (DLP, Lithography, SLA, …)

Each face is now divided into four triangles by halving the edges. The middle triangle is extruded to a new regular tetrahedron. This is iteration 2.

At each tip of the primary tetrahedron, the process is repeated for the three new, smaller triangles formed by the outer edge of the most recent tetrahedron, avoiding collision of the newly generated tetrahedrons.

One manifestation, the file KFrac01-6, representing 6 iteration steps, is shown in Figure A.2. A truncated structure is also provided that is useful for all methods requiring support structures, as the details facing downwards cannot be realized in those.

The resulting structure has iterating edge lengths divided by two for each step, given in Table A.1 for the first 10 iterations.

In order to apply the structure, it should be placed with one side of increasing detail pointing upward (z-direction) and two aligned in x-direction. Support structures can be added if necessary.

The structure can be scaled appropriately for larger systems, but highest iteration should always have a dimension below Ra.

This fractal is an easy way to evaluate the resolution limit of an AM system. If the smallest realized edge-length is below Ra, the highest possible resolution can be determined by simply counting the number of tetrahedrons realized in a satisfactory way and looking up the corresponding dimension in Table A.1, or calculating it accordingly, considering any scaling operations performed. The advantage compared to regular, cube structures is that real-world-like but regular details are given that challenge the printing process in all three directions at the same time.

Table A.1 — Edge lengths for the first 15 iterations of a Koch-Flake-like Tetrahedron structure, starting with 10 mm edge length with resulting edge length of smallest detail

Iteration step	Number of Tetrahedrons per face	Edge length [mm]
1	0	10
2	1	5
3	2	2.5
4	3	1.25
5	4	0.625
6	5	0.3125
7	6	0.15625
8	7	0.078125
9	8	0.0390625
10	9	0.01953125
11	10	0,009765625
12	11	0,0048828125
13	12	0,00244140625
14	13	0,001220703125
15	14	0,0006103515625

A.3 Test structures for Process accuracy

To test for process accuracy, the use of the files described under “cubes” is recommended, additional qualifications using sphere, tetrahedron or petal are useful depending on the intended application. For example, spheres and petals should be used if curved structures are an important product of the AM process. The choice of structure should be justified in the report.

A.3.1 Cubes

The recommended geometries are “**6 cubes.stl**” and “**6 cubes-xyz.stl**”.

Cubes for determining process accuracy are made as simple cubes with 1 cm edge length and assembled with parallel sides and meeting exactly at their points (Figure A.3).

For printing, they should be oriented with edges parallel to x and y sides and the vertical edge in z-direction.

To evaluate the printed structures, use the appropriate system, either direct measurement with calibrated tools or microscopic procedures with digital evaluation. Flat sheets are useful for distance measurements for Ad 2 of z-stacked cubes.

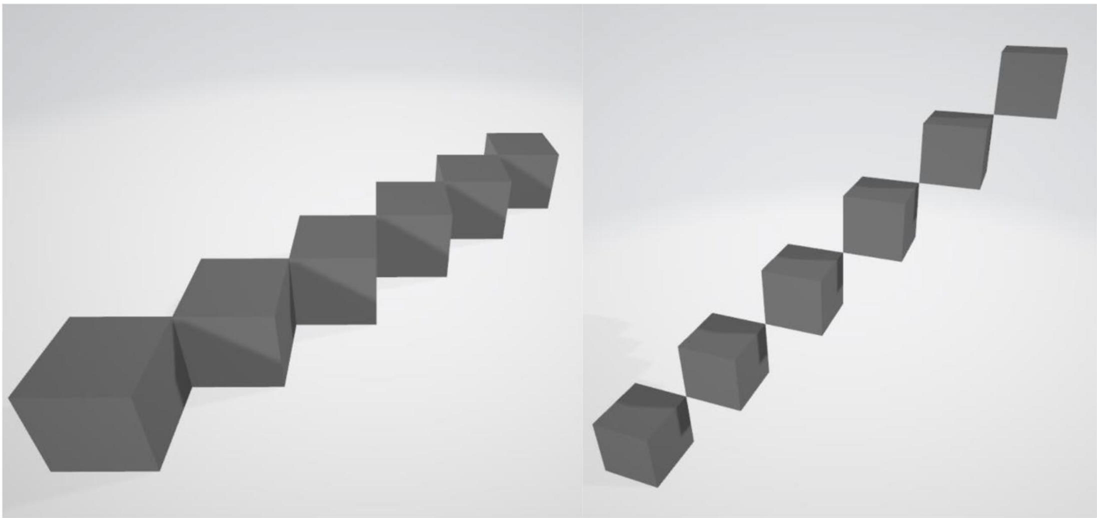


Figure A.3 — xy-stacked (left) and xyz-stacked (right) cubes for process accuracy measurement

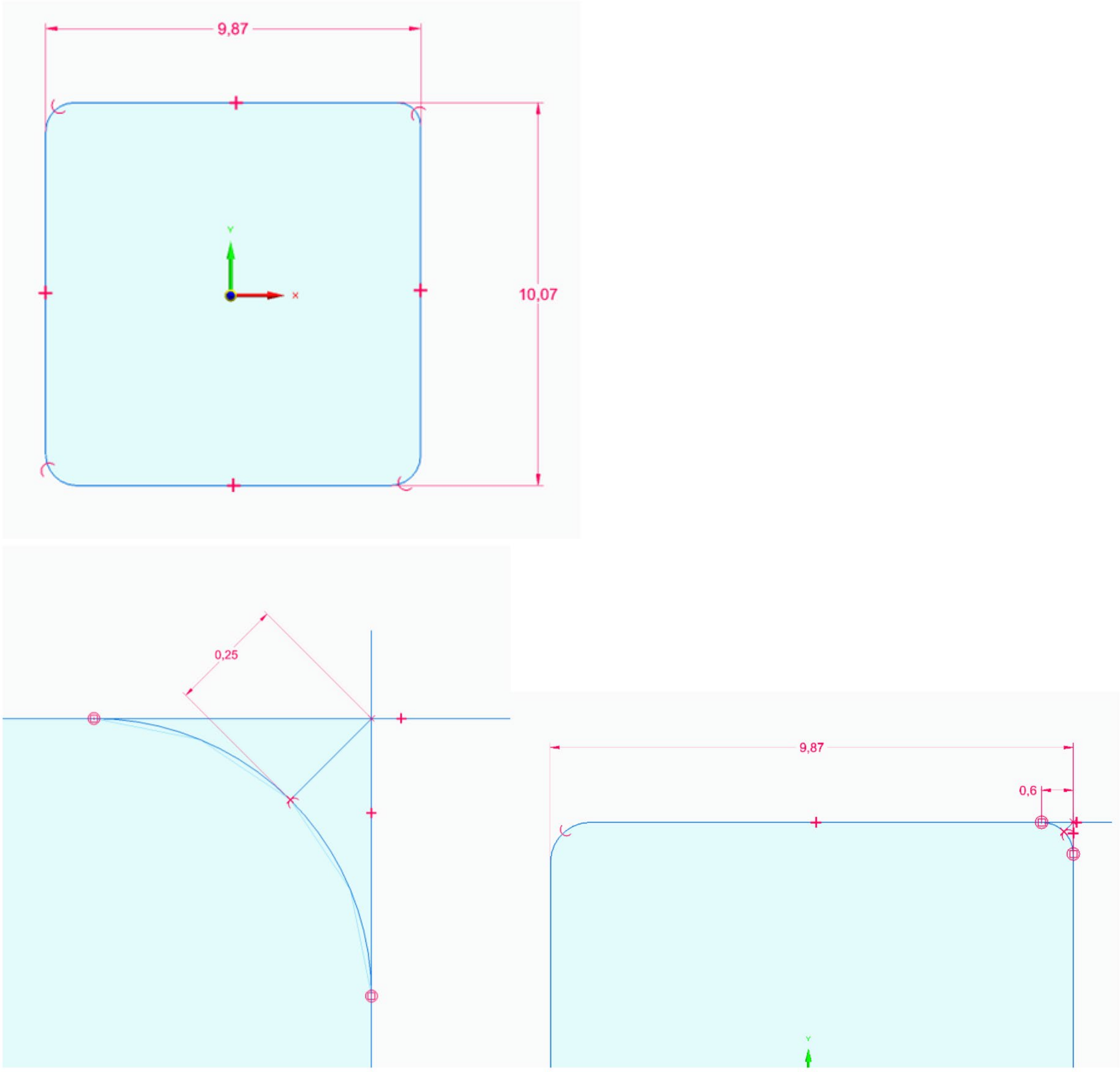


Figure A.4 — Measurements on cubic structures. Each structure is regarded in on of the three Euclidean planes and the actual distances of sides measured to determine Ad 1, their relation to determine Ar (top). For At determination, the lines given by the straight edges can be prolonged to mark the theoretical tip. At can then be determined either as distance along the angle bisector from theoretical tip to begin or printed structure (left), or as ratio between distance from the point, were the deviation (curve) starts to the theoretical tip (right)

A.3.2 Sphere

The recommended geometry is “**Sphere_10mm.stl**”, but modifications might be necessary.

Spheres are challenging structures for AM systems since curves are discretized when adapted to the printing resolution. In systems that use splines (like FDM systems in the xy-plane or robot arms), the accuracy of curves, given by Ar, are challenged by the synchronization of the movement of the different axis.

For a perfect sphere, it is hard to measure the exact dimensions in x,y,z-direction, but in the reality of additive manufacture, resolution boundaries produce flat planes at least in z-direction (e.g. for FDM printing and guided laser lithography) and also in x,y-direction (powder-bed and DLP/lithographic printing). The actually realized dimensions can be measured in reference to these planes.

As an alternative, spheres can be marked or connected to the base plate to determine the x, y and z planes orientation. In this case, care shall be taken not to cross the points of the maximum x/y/z-extension that have to be measured.

A.3.3 Tetrahedrons

The recommended geometries are "**Tetrahedron_10mm**" and "**KFrac01_15-half.stl**".

The tetrahedron, alternatively the KFrac-01 structure, can be placed with one side in x direction and used for several measurements. The advantage is that the ability of the printing system to realize diagonal structures is tested. On a tetrahedron the following measurements can be made, here with theoretical values for the standard structure:

h) Length of sides (10 mm)

i) Distance from x-edge to furthest point in y-direction (8.66 mm rounded)

j) Height in z-direction (8.17 mm rounded)

k) Angle between two edges in the plane of the corresponding face (60°)

For reference, see Figure A.5.

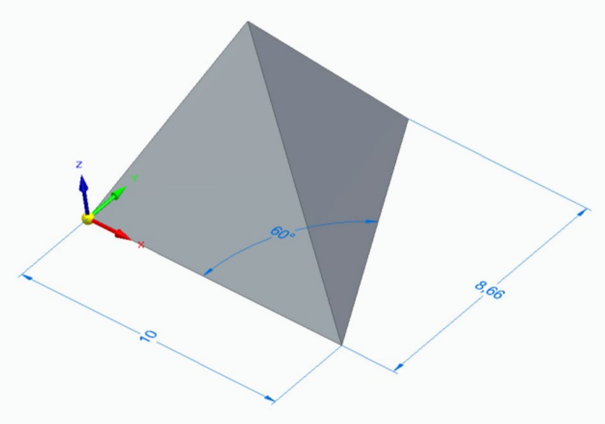


Figure A.5 — Analysis of a printed tetrahedron with exemplary distances

The tip can also be analyzed in the same way as for cubes by documenting each face in direct view, perpendicular to the surface.

A.3.4 Petal

The recommended structure is "**8-Petal_10mm.stl**".

The standard petal structure allows the analysis of tip and arc realization in the x- and y-axis and in the 45° angle bisectors between them. It is constructed by drawing a 20 mm line in x direction, crossed by a 10mm orthogonal line in the middle, then two arcs that extend from the endpoints of the longer line, crossing the endpoints of the shorter line (Figure A.6). The resulting bows are copied by 7 45 °C rotations around the starting point. The surface is extruded by 10 mm to result in a 3D body that can be printed lying flat on the xy-plane or standing upright in either in the xz- or yz-plane. In any case, two petal tips should be aligned with each one of the axis.

The structures can be used to determine At by extending the arcs over an image of the printed part. By overlying the theoretical with the actual image, fidelity of the arc realization can also be evaluated as percentage of area coverage (not detailed in the table).

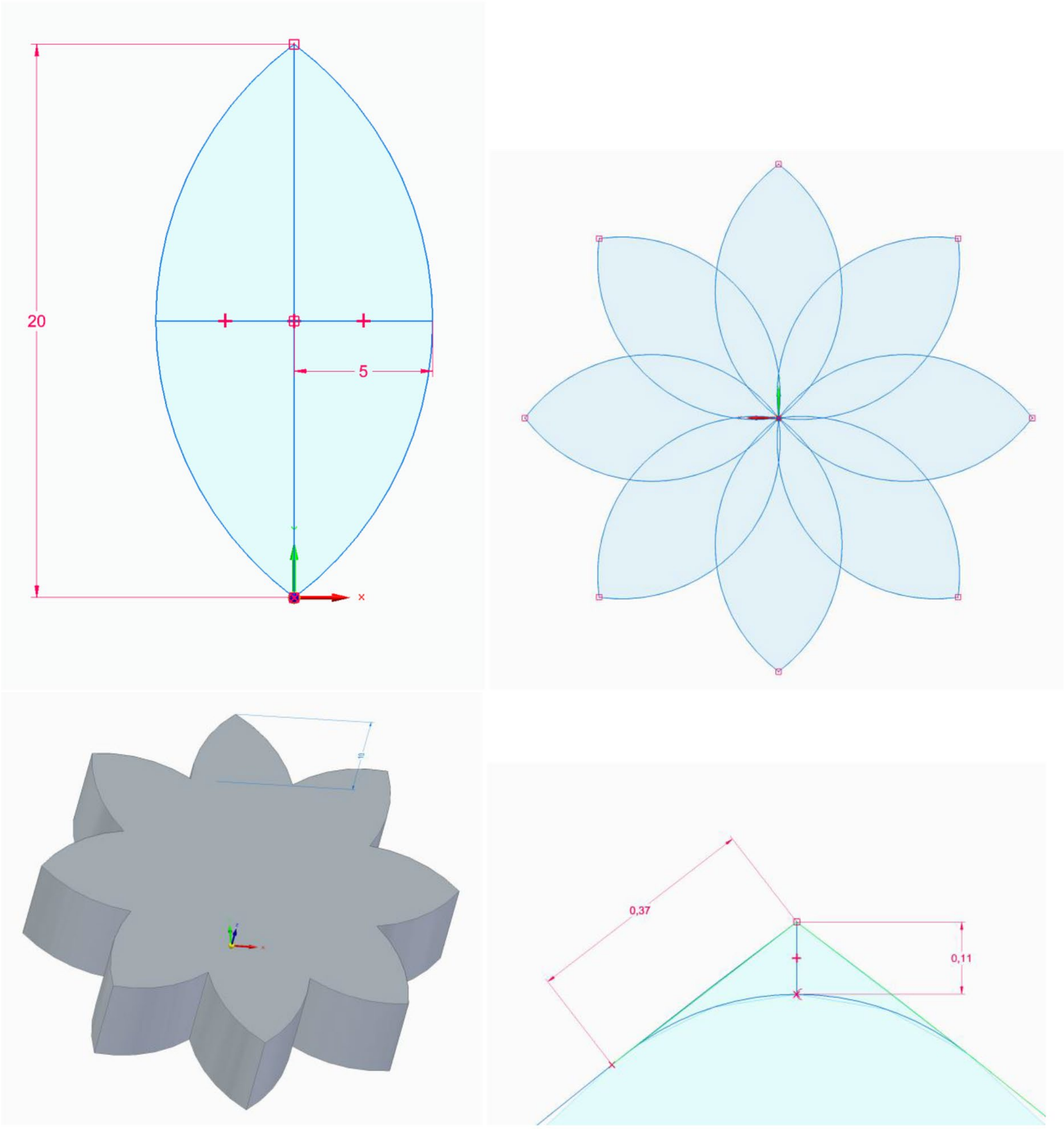


Figure A.6 — Construction of the petal structure (top), an image of the 10 mm 3D-extrusion body (lower left) and an example for measuring At on one of the tips

A.4 Evaluation of the structures

For evaluation, proceed as described in Table A.2. The accuracies shall be calculated as mean (of modulus) with standard deviation from several measurements and can be given as rational number between 0 and 1 or percentage.

Each value should be reported with reference to the material, printer and protocol used. This includes the use of any support material and a description of the support structures employed.

For multimaterial evaluations, the methods described for single materials can be combined for structures printed from units multiplied from the standard geometries.

For any multimaterial analysis, the number of materials combined in the print should be given, and the entire analysis should be presented as one report together for all materials.

Table A.2 — Parameters analyzed for different test structures for accuracy determination; each value shall be calculated as mean with standard deviation. Negative values have to be multiplied by -1 before calculating the means

Structure	Distance	Results	Calculated Accuracy
xy-stacked cubes; xyz-stacked cubes, sphere	edge length for each object; use the same reference edge for all	x, y, z length $l_{x,y,z}$ for each cube; theoretical value $t_{x,y,z}$ = 10 mm	**Ad 1** = |(10-l)/10| for each axis; x100 for %
xy-stacked cubes; xyz-stacked cubes	x, y, z from 0 (tip of first cube) to furthest edge of each cube	x, y, z distance $d_{x,y,z}$ for each cube; theoretical values $t_{x,y,z}$ = 10/20/30/40/50/60 mm	**Ad 2** = |(t-d)/t | for each axis; x100 for %
xy-stacked cubes; xyz-stacked cubes; spheres	ratio Ar between Ad 1 for two dimensions ($Ar_{x,y}$ / $Ar_{x,z}$ / $Ar_{y,z}$)	relation of actual ratio to 1	**Ar** = |1- l_x/l_y | etc. for each ratio; x100 for %
Cubes, tetrahedrons, petals	Coverage of an acute tip: distance along angle bisector from actual tip to meeting point of prolonged edges of structure when viewed in on 2D perspective	distance At-d in mm	**At 1** = distance in mm of realized to expected tip; equals reduction of acute structures
Cubes, tetrahedrons	Coverage of an acute tip: distance from theoretical tip to first correct point to total distance	distance r from theoretical tip to structure in mm along the continued edge line with measured length l	**At 2** = (l – r)/l; x 100 for %
Cubes, tetrahedrons, petals	Coverage of an acute tip: relative area coverage, determined by image analysis	Area F_m covered by structure; F_t is expected area, both in mm^2	**At 3** = $(F_m-F_t)/F_t$; x 100 for %
Cubes, tetrahedrons, petals	angle between two edges in one 2D plane of viewing	angle in °	**Aa** = ratio of angle measured to expected angle; x100 for %

Bibliography

[1] CWA 18130:2024, *Standardized scaffolds library for tissue engineering research and industrial applications*