

Reference Artefacts and Benchmark Geometries for Additive-Manufacturing Qualification

Measurands, traceability and fitness for purpose

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Abstract

Additive-manufacturing test artefacts compress many geometric features into one build, but a dense collection of cones, holes, walls and overhangs is not automatically a qualification method. Each feature needs a declared measurand, a measurement route, an uncertainty compatible with the decision and a reason for occupying a particular position and orientation. Otherwise the artefact is a demonstration piece whose attractive complexity can conceal ambiguous evidence.

This review develops a fitness-for-purpose architecture for reference artefacts and benchmark geometries used in additive-manufacturing qualification. It distinguishes a digital nominal definition, a manufactured test artefact, a calibrated reference object and a routine witness feature. It links feature selection to geometric capability, spatial effects, surface response and minimum-feature claims; addresses file identity, specimen state, measurement access, uncertainty and repeated builds; and defines boundaries between characterisation, calibration, monitoring and acceptance. ISO/ASTM 52902 and the NIST additive-manufacturing test artefact provide established foundations, while the wider literature shows that no single geometry serves every process and decision. The central conclusion is that an artefact is useful only when every retained feature closes a traceable question. Qualification belongs to the coupled design-build-measure-decision chain, not to the geometry alone.

Keywords: test artefact; benchmark geometry; additive manufacturing; geometric capability; traceability; measurand; uncertainty; minimum feature; qualification; fitness for purpose

1. Significance and scope

Direct measurement of every internal machine characteristic is often impractical. A manufactured test artefact provides a composite test in which machine, process, material and data preparation contribute to the resulting geometry. This is both its strength and its limitation. The artefact samples actual production, but one observed deviation may have several possible causes.

A qualification programme should therefore begin with the decision: compare systems, accept a newly installed machine, map a build volume, monitor drift, evaluate a material change or demonstrate a product-relevant capability. The decision determines the artefact and measurement plan.

1.1 Corpus boundary

ER-210 owns reference artefacts and benchmark geometries for additive-manufacturing qualification. ER-010 owns cross-scale metrology of vat photopolymerisation. ER-203 owns radiometric and actinometric traceability for photopolymer processing. ER-209 owns interlaboratory round-robin design for vat-photopolymer materials. ER-297 owns calibration management for photopolymer production and testing. ER-344 owns machine-capability studies for additive manufacturing. ER-210 supplies measurable geometries to those workflows but does not replace their calibration, statistical or method-specific requirements.

2. Four objects that should not be confused

- 1 **Digital nominal definition:** the controlled CAD model, drawing, coordinate system and semantic tolerances.
- 2 **Manufactured test artefact:** the physical output of one declared machine-process-material state.
- 3 **Calibrated reference object:** a stable object with assigned values and uncertainties used to check a measurement system.
- 4 **Routine witness feature:** a small coupon or geometry included in production builds to monitor a bounded response.

A printed artefact is not a dimensional reference merely because its CAD file is exact. Its deviations are normally the measurement outcome. Conversely, a calibrated reference object need not resemble the AM process if its purpose is to verify the measuring instrument.

3. Start with measurands

Each feature should map to one or more explicitly defined measurands: size, form, location, orientation, surface texture, wall continuity, hole clearance, unsupported-angle survival or another observable. State datum system, filtering, fitting rule, sampling, environmental conditions and whether material is added or removed before measurement.

For a dimensional feature i , a basic signed deviation is:

$$\sqrt{d_i = y_i - x_{\{i, \text{nom}\}}}$$

where y_i is the measured value and $x_{i,nom}$ is the controlled nominal value. This simple expression is incomplete unless the measurement uncertainty, alignment, thermal state and nominal-definition uncertainty are also known.

4. Feature-to-question mapping

The NIST design rules favour simple features that are easy to define and measure, span orientations, include holes and bosses, and can reveal limitations without excessive build time or material [1]. ISO/ASTM 52902 describes suites of test geometries for assessing geometric performance, surface finish and minimum feature sizes and leaves the specific measurement method to the user [2].

Useful feature families include:

- 1 external and internal cylinders for size and roundness;
- 1 planar steps for scale and axis response;
- 1 holes and bosses for sign-dependent compensation;
- 1 thin walls, pins and gaps for minimum positive and negative features;
- 1 ramps or inclined planes for layer-direction surface response;
- 1 position patterns for location and build-volume effects; and
- 1 repeated simple features for within-build spatial comparison.

Every feature that lacks a measurement and decision should be removed. Complexity without a question adds cost and ambiguous failure modes.

5. Digital master and nominal integrity

The digital package should contain the authoritative native or neutral solid model, drawing, units, coordinate system, datums, intended orientation and a checksum. Tessellation settings and any subsequent repair, scaling or slicing transformations must be recorded. A visually identical mesh can differ geometrically at curved boundaries.

Nominal values used in analysis should come from the controlled definition, not from a later reverse-engineered mesh. If machine compensation is applied, distinguish commanded geometry from uncompensated design. Preserve both when the comparison requires them.

6. Build layout and spatial coverage

One artefact at the centre does not map the build volume. Options include one large artefact spanning the platform, multiple small artefacts at fixed coordinates, or a modular library of features distributed by design. The choice depends on whether gradients, local distortion, exposure non-uniformity or process economics dominate.

Position and orientation should be treated as design factors. Replicated features at different locations estimate spatial variation, not repeatability by themselves. Repeatability requires repeated builds under the same declared conditions and comparison at corresponding locations.

7. Material, supports and post-processing

Geometric capability belongs to a machine-process-material state. Resin optical properties, viscosity, ageing and post-cure shrinkage can change results. Report material lot, open-vat history, environmental conditions, build parameters, support contacts, separation, washing, drying, post-cure and elapsed time at measurement.

Features intended to characterise as-built capability should minimise manual intervention. If supports or polishing are necessary, their locations and removal method become part of the test. A feature damaged during removal cannot be interpreted solely as a printing limitation.

8. Measurement access and method selection

Artefact design should be co-developed with the measurement plan. A deep internal hole may be manufacturable yet inaccessible to the selected instrument. Flexible photopolymers can deform under contact probing. Translucent surfaces can challenge optical edge detection. CT can access internal features but introduces reconstruction and surface-determination models.

Use method-specific fixturing and datums that do not conceal the feature. Compare contact, optical and volumetric methods only after defining equivalent measurands. The extensive benchmark-artifact literature shows recurring feature families but also wide variation in process, material and measurement purpose [3].

9. Traceability and uncertainty

Metrological traceability is a property of a measurement result connected to references through a documented, unbroken calibration chain, with each link contributing uncertainty [4]. A traceable instrument does not make an ill-defined measurand traceable.

For a result model $y=f(x_1,\ldots,x_n)$, a first-order combined standard uncertainty may be expressed as:

$$u_c(y) = \sqrt{\sum_{i=1}^n \left(\frac{\partial f}{\partial x_i} \right)^2 u^2(x_i) + 2 \sum_{i < j} \frac{\partial f}{\partial x_i} \frac{\partial f}{\partial x_j} \frac{\partial^2 f}{\partial x_i \partial x_j} u(x_i) u(x_j)} \quad \text{[5]}$$

Contributors can include scale calibration, probing or imaging, temperature, alignment, fitting, surface determination, repeat positioning and nominal definition. The Guide to the Expression of Uncertainty in Measurement provides the general framework [5]. Measurement capability should be adequate for the tolerance or comparison being made; otherwise the artefact may reveal only the measurement system.

10. Minimum-feature claims and censored outcomes

A wall that exists at one location in one build does not establish a minimum printable wall. Define success, inspection method and continuity. Test a sequence of sizes across builds and positions. Positive and negative features should be treated separately because cure spread and cleaning affect them differently.

When a feature cannot be measured because it fused, broke or failed to form, the outcome is informative and should not be entered as zero or omitted. Record it as a categorical or censored result. The threshold is conditional on material, orientation, location, post-processing and inspection capability.

11. Repetition and capability evidence

A qualification artefact should be produced in enough independent builds to estimate temporal variation. Within-build replication reveals spatial effects and local scatter. Between-build replication reveals changes in setup, material condition and process stability. Between-machine comparison adds another level.

Do not calculate a capability index from a mixed or drifting process. First assess stability, measurement adequacy and distribution. A benchmark can compare systems without supporting formal production capability. ER-344 retains the dedicated machine-capability boundary.

11.1 Attribution and diagnostic limits

A composite artefact response can suggest error mechanisms but rarely proves them. Opposite deviations in holes and bosses may indicate compensation or threshold effects; location patterns may indicate scale, projection or mechanical non-uniformity; orientation-dependent slopes may indicate layer or support effects. Confirmation requires targeted measurements or controlled parameter changes.

Moylan and co-workers designed the NIST artefact to connect simple measurable features with system capabilities and limitations, while recognising that composite tests can make source attribution difficult [1]. The artefact should be used to generate hypotheses and quantify performance, not to replace root-cause experiments.

12. Interpretation matrix

Intended use	Suitable artefact property	Required evidence	Unsupported leap
New-machine acceptance	Stable nominal features tied to contractual measurands	Agreed build state, measurement method, uncertainty and decision rule	General product qualification
Build-volume mapping	Repeated features at fixed coordinates	Spatial design and repeated builds	Long-term capability from one map
Material-change comparison	Same digital definition and controlled machine state	Baseline, changed material and state equivalence	Cause assigned to chemistry alone
Routine monitoring	Small sensitive witness with control limits	Established baseline and measurement stability	Full recalibration of the system
Cross-system benchmark	Portable geometry and harmonised measurement	Common definitions, protocol and uncertainty	Ranking every application with one score

13. Minimum reporting set

Report intended decision; artefact class; design-file identity and hash; drawing, units, coordinate system and datums; feature-to-measurand map; material and specimen state; build layout, orientation and parameters; supports and post-processing; measurement method, fixturing, alignment and environmental conditions; calibration chain; uncertainty; repeated builds and locations; treatment of failed or unmeasurable features; raw and processed data; decision rule; and limits on transfer.

The NIST public artefact package includes controlled geometry and an inspection worksheet and explicitly frames its use around documented process settings and measured deviations [6]. Such auxiliary records are part of the evidence system, not optional paperwork.

14. Knowledge boundary

Existing test artefacts and benchmark reviews establish useful feature families and design principles, but they do not establish one artefact that has been validated across all additive-manufacturing processes, materials, machine architectures and qualification decisions. Published comparisons also do not provide a universal conversion from artefact performance to product conformity or long-term process capability. Transfer therefore requires a documented relationship among the intended decision, the selected features, the measurement route and the production state.

15. Limitations

No single artefact can sample every geometry, material, process and failure mode. Large artefacts consume time and can introduce thermal or optical interactions absent from production parts. Small artefacts may miss build-volume effects. Measurement accessibility can bias feature selection. A benchmark result can become obsolete after software, optics, calibration, resin or post-processing changes. Passing an artefact test does not establish fitness of an unrelated product without a justified relationship.

16. Conclusions

A qualification artefact is a structured set of questions embodied in geometry. Its value comes from defined measurands, controlled nominal data, representative material and state, measurable features, adequate uncertainty and a decision rule. Reference object, printed test artefact, benchmark geometry and routine witness are different roles. Repeated builds and spatial sampling are required to distinguish local appearance from capability. The strongest artefact is not the most complicated one; it is the smallest design that answers the required qualification questions without ambiguous measurement or transfer.

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