**WERKSTOFFWERK · CRITICAL ENGINEERING PAPER**

*Public strand · with references · no marketing*

# Capabilities and Limits of Additive Manufacturing

*An honest engineering assessment: physical properties, tolerances, reproducibility, service life and the case for and against AM versus classical manufacturing*

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### Stance of this paper

This paper assesses additive manufacturing honestly, scientifically and critically – explicitly BEFORE any marketing. It names genuine strengths and genuine limits in equal measure.

Specific figures are orientation values and strongly process-, material- and parameter-dependent. They do not replace part-specific qualification. Schichtwerk is a contract manufacturer; the suitability decision rests with the customer.

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# 1. Introduction: honest rather than euphoric

Additive manufacturing (AM, colloquially 3D printing) is often presented in marketing as universally superior. From an engineering standpoint this is inadmissible. AM is a manufacturing process with a characteristic profile of strengths and equally characteristic, often underestimated, limits. This paper separates demonstrable capabilities from advertising claims and provides a basis for deciding when AM is sensible and when classical processes remain superior.

**Guiding principle**

AM does not replace classical manufacturing; it complements it. Value arises where its specific strengths (complexity, individualization, tool-free production) are needed – not as a blanket substitute.

# 2. AM as a Manufacturing Class – Classification

Manufacturing processes are classically divided per DIN 8580 into six main groups (primary shaping, forming, separating, joining, coating, changing material properties). Additive manufacturing is a primary-shaping process that builds geometry layer by layer from formless material. ISO/ASTM 52900 defines seven process families: material extrusion (FDM/FFF), vat photopolymerization (SLA/DLP/MSLA), powder bed fusion (SLS/MJF/DMLS), binder jetting, material jetting, directed energy deposition and sheet lamination. [1]

This classification is decisive: AM is not a single process but a class of very different processes, each with its own properties, tolerances and limits. Statements about “3D printing” in general are therefore almost always too sweeping.

# 3. Genuine Capabilities (sober)

The following strengths are real and grounded in process physics – not in marketing:

- Geometric freedom (freeform): internal channels, undercuts, lattice structures, topology-optimized parts that cannot be produced by machining or injection moulding.
- “Complexity for free”: unit cost rises primarily with volume/time, barely with shape complexity.
- Tool-free: no mould/tooling cost – economical for one-offs and small series, fast iteration.
- Individualization: each part can differ at no extra cost (patient-specific, spare parts on demand).
- Function integration and lightweighting: several components as one part; material only where load acts.

**But**

Each of these strengths is conditional. “Freeform” does not mean arbitrary: overhangs need supports, channels must be drainable, thin walls are process-limited. Economics tip toward classical processes as quantity rises.

# 4. Physical Properties and Their Limits

## 4.1 Anisotropy – the central limit

The most important mechanical limitation of FDM is anisotropy: parts are markedly weaker in the build direction (Z) than in the layer plane (XY), because Z-strength depends on the diffusion welding (reptation) of adjacent layers. Z tensile strength typically reaches only about 40–70 % of XY strength. A marketing “strength value” without a direction is therefore incomplete. [2]

## 4.2 Further physical limits

| Property | Limit / effect |
|---|---|
| Porosity | internal voids → fatigue weak points, hard to inspect non-destructively |
| Surface | layer lines; FDM Ra ~10–25 µm, SLA much smoother; post-processing needed |
| Residual stress/warping | thermal gradient → warping, dimensional deviation on large parts |
| Layer adhesion | Z-strength process-dependent (temperature, speed) |
| Heat deflection | material-dependent; PLA ~55–60 °C → not for hot environments |
| Creep | thermoplastics creep under sustained load, especially near glass transition |

## 5. Tolerances and Tolerance Classes

Achievable dimensional tolerances are process-dependent. FDM practically reaches about ± 0.3–0.5 mm or ± 0.5 % of nominal length; SLA/DLP is more accurate (about ± 0.1–0.2 mm). For comparison: machining reaches ISO tolerance grades IT6–IT7, injection moulding tight, reproducible tolerances. General tolerances per ISO 2768 (fine f / medium m / coarse c) are often met by AM parts only in the coarse class, and rarely in the fine class without post-processing. [3]

**Design consequence**

Fits, threads and sealing faces should not be toleranced “as printed” but machined afterwards or solved with inserts (threaded inserts).

Tolerance specifications on the drawing must consider the process – unrealistically tight tolerances create scrap.

## 6. Reproducibility and Quality Assurance

AM parts show greater batch-to-batch variation than established series processes. Properties depend on machine, material batch, humidity, nozzle/exposure parameters, orientation and post-treatment. Without a validated, frozen process, reproducible mechanical values are not guaranteed. This is precisely why regulatory guidance for critical parts demands process validation with defined acceptance criteria. [4]

- Document per part: material+batch, machine, parameter profile, orientation, post-treatment, inspection.
- First-article inspection per new part; statistical process control of critical dimensions.

## 7. Service Life and Ageing

Polymer AM parts age. Relevant mechanisms: UV radiation (embrittlement, discoloration, especially PLA/PETG outdoors), hydrolysis (PLA is biodegradable and thus moisture/temperature-sensitive), thermal softening (PLA from ~55–60 °C), creep under sustained load and fatigue at internal defects. There is no blanket “service life” – it is a function of material, load, temperature, medium and geometry. [5]

**Honest material statement**

PLA is an excellent prototyping and decorative material, but unsuitable for permanently loaded or warm/humid/outdoor applications.

For higher demands: PETG, ABS/ASA, PA, PC or filled materials – each with its own limits (see WERKSTOFFWERK FDM/SLA).

## 8. Test Methods

| Test | purpose | standard/note |
|---|---|---|
| Tensile test | mechanical values per direction | ISO 527 (plastics), specimen in XY and Z |
| Dimensional check | tolerance compliance | gauges/3D scan, ISO 2768 reference |
| CT / X-ray | porosity, internal defects | non-destructive, for critical parts |
| Surface | roughness Ra/Rz | stylus profilometry |
| DSC/TGA | glass transition, cure degree, material ID | thermal analysis |
| Fatigue/durability | service life under load | application-near, costly |

## 9. Critical Components – when AM is not suitable

For safety-critical, load-bearing or fatigue-loaded components, particular caution is warranted. Anisotropy, porosity and batch variation directly affect failure safety here.

**Caution warranted for**

load-bearing structural parts whose failure endangers persons (without qualification/proof),
pressure vessels and fatigue-loaded parts,
parts with tight fits or sealing functions without post-processing,
medical/construction applications without material approval and a validated process (see ANWENDUNGSWERK).

This is not an exclusion but a condition: with qualified material, a validated process, suitable orientation and inspection, demanding parts can also be made – but the effort for this is real and must not be marketed away.

## 10. Sensibility: Decision Framework

| AM makes sense when … | Classical is better when … |
|---|---|
| geometry is complex/freeform | geometry is simple |
| quantity is small (1–100s) | quantity is large (1000s+) |
| individualization is needed | parts must be identical |
| fast iteration matters | tightest tolerances matter |
| no tooling is economical | series tooling amortizes |
| lightweighting/integration adds value | standard stock suffices |

## 11. AM vs. Classical Manufacturing – Overview

| Criterion | AM (FDM/SLA) | Machining | Injection moulding |
|---|---|---|---|
| Geometric freedom | very high | medium | low (demoulding) |
| Tolerance | coarse–medium | very fine (IT6–7) | fine, reproducible |
| Unit cost single part | low | medium–high | very high (tooling) |
| Unit cost mass series | high | medium | very low |
| Reproducibility | medium (validatable) | high | very high |
| Tooling cost | none | low | very high |

## 12. Other Processes and Materials (brief)

For context – without leaving the focus: powder-bed processes (SLS/MJF) yield support-free, more isotropic parts with better Z-strength than FDM; metal AM (DMLS/LPBF) achieves load-bearing metal parts but requires inert gas, supports and extensive post-processing. On the material side the spectrum ranges from PLA/PETG/ABS/ASA/PA through fibre-reinforced (CF/GF) and photopolymers to metals and bio-hydrogels. Each process-material pair has its own tolerance, strength and ageing profile; the critical assessment of this paper applies analogously to all.

## 13. Synthesis

Additive manufacturing is a valuable, distinct manufacturing class with a clear strength profile – geometric freedom, tool-free production, individualization. Its limits – anisotropy, coarser tolerances, greater variation, material-dependent ageing – are equally real and are routinely understated in marketing. A serious application chooses the process by part requirement, not by fashion, qualifies critical parts, specifies tolerances appropriately for the process and communicates limits honestly. This very honesty is, in the long run, a greater competitive advantage than any overpromise.

## Declarations

Conflict of interest: The author operates Schichtwerk, a service company in additive manufacturing, and thus has an economic interest in the process. This paper has been deliberately kept critical and marketing-free to counteract this conflict.

*Suggested citation: [Nachname] T. Capabilities and Limits of Additive Manufacturing – an Honest Engineering Assessment. Paper, Version 1.0. Schichtwerk; 2026.*

# References

**[1]** ISO/ASTM 52900:2021. Additive manufacturing – General principles – Fundamentals and vocabulary. Geneva: ISO; 2021. DIN 8580:2003 Fertigungsverfahren – Begriffe, Einteilung.

**[2]** Gibson I, Rosen D, Stucker B, Khorasani M. Additive Manufacturing Technologies. 3rd ed. Cham: Springer; 2021. (Anisotropie, Schichthaftung, Reptation).

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**[4]** U.S. Food and Drug Administration. Technical Considerations for Additive Manufactured Medical Devices. Silver Spring: FDA; 2017. (Prozessvalidierung, Reproduzierbarkeit).

**[5]** Wittbrodt B, Pearce JM. The effects of PLA color on material properties of 3-D printed components. Addit Manuf. 2015;8:110–116; sowie Literatur zu PLA-Hydrolyse und UV-Alterung.

**[6]** ISO 527 (Zugversuch Kunststoffe); ISO 178 (Biegeversuch). Prüfkörper-Orientierung XY/Z. CEN/ISO.