SCHICHTWERK · WERKSTOFFWERK

FDM / FFF

Engineering Reference – Polymer Technology

Fundamentals · Materials Science · Metrics · Post-processing · Finishing · Surface Quality

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Part 1 · FDM/FFF Process Fundamentals

1.1 Working principle

In Fused Deposition Modeling (FDM), also Fused Filament Fabrication (FFF), a thermoplastic filament is extruded through a heated nozzle and deposited layer by layer. The material is processed above its glass-transition or melting temperature, fuses with the layer below and solidifies on cooling. Part strength arises from intermolecular diffusion (reptation) at the layer interfaces.

1.2 Process chain

Phase	Step	Critical quantity
Preparation	CAD → STL/3MF → slicing	tolerance, resolution, orientation
Material handling	drying, storage	residual moisture (hygroscopic polymers)
Extrusion	melting, conveying	nozzle temperature, volume flow
Layer build	deposition, fusion	interlayer adhesion (Z-strength)
Cooling	solidification, shrinkage	warping, residual stress
Post-processing	support removal, finish	surface quality, dimensional accuracy

1.3 Machine kinematics

- Cartesian (bed-slinger / gantry): most common, robust.
- CoreXY: high speeds with low moving mass.
- Delta: fast, circular, high build height.

Part 2 · Materials Science of Thermoplastics

2.1 Polymer classes

Thermoplastics divide into amorphous (no defined melting point, glass transition Tg) and semi-crystalline (melting point Tm, crystallization tendency) materials. This classification governs processing and shrinkage behaviour.

Polymer	Structure	Tg (°C)	Tm (°C)	Shrinkage	Warping
PLA	amorph./semi-cryst.	55–65	150–160	low	low
PETG	amorphous	78–85	—	low	low
ABS	amorphous	105	—	medium	high
ASA	amorphous	100–110	—	medium	high
PA6	semi-crystalline	45–60	215–220	high	high
PC	amorphous	145–150	—	medium	high
TPU	elastomer	-30 to -50	—	low	low

2.2 Mechanical properties (XY reference)

Material	Tensile MPa	E-mod GPa	Elong. %	Impact kJ/m²	HDT °C
PLA	45–65	3.5–4.0	2–6	3–8	52–60
PETG	50–65	2.0–2.8	8–20	6–12	70–80
ABS	40–60	1.8–2.4	6–20	8–15	88–98
ASA	45–65	1.8–2.5	6–18	8–15	90–100
PA6-CF	80–120	5.0–8.0	2–5	6–14	120–180
PC	55–75	2.0–2.4	8–15	25–45	110–135
TPU 95A	30–50	0.01–0.05	300–600	no break	65–75

2.3 Fibre reinforcement & moisture

Hygroscopy – critical practical factor

PA, PC, PVA, TPU strongly absorb humidity → bubbles, stringing, strength loss.
Drying before printing: PA 70–80 °C/6–12 h, PC 80–100 °C/4–6 h, PETG 60–65 °C/4 h.
Store in dry box with silica gel; aim for residual moisture < 0.2 %.
Short-fibre CF/GF (10–30 wt%) raise stiffness, lower elongation; abrasive → hardened nozzle required.

Part 3 · Process Metrics & Parameters

3.1 Key parameters

Parameter	Typ. range	Effect on ...	Trade-off
Layer height	0.08–0.30 mm	surface, Z-resolution, time	fine ↔ fast
Nozzle temperature	upper mfr band	interlayer adhesion, Z-strength	strength ↔ stringing
Print speed	40–300 mm/s	time, surface, accuracy	fast ↔ quality
Wall count	2–4+	strength, tightness	strong ↔ material/time
Infill density	15–100 %	weight, strength	light ↔ strong
Cooling	0–100 %	overhang, adhesion	detail ↔ Z-strength
Flow multiplier	0.95–1.05	accuracy, density	over/under-extruded

3.2 Anisotropy quantified

FDM parts are direction-dependent. Z-strength (across layers) typically reaches only 40–70 % of XY-strength, since layer bonding here relies on diffusion rather than the polymer matrix. Higher nozzle temperature, lower cooling and thinner layers improve Z-bonding.

Orientation	Rel. tensile strength	Recommendation
XY flat	100 % (reference)	standard for most load cases
XZ / on-edge	often highest UTS	high tensile load in layer direction
Z upright	40–70 %	avoid Z-load, critical for threads

3.3 Reproducibility

Measures for reproducible results

Manage filament by batch, document drying status.
Treat nozzle as wear part (CF/GF: replace more often).
First-article inspection per new part.
Maintain calibration objects (flow, temperature, retraction) per material.
Archive print record: profile, batch, machine, date.

Part 4 · Post-processing

4.1 Support removal

- Soluble supports (PVA, BVOH, HIPS): water/limonene-soluble, ideal for complex geometry.
- Break-away supports (same material): mechanical removal, contact-surface rework needed.

4.2 Mechanical post-processing

Method	Suitability	Note
Sanding (dry/wet)	all thermoplastics	wet preferred (dust); grit 200→2000
Filling/priming	PLA, PETG, ABS	fill layer lines before paint
Milling/drilling	PC, PA, ABS	sharp tool, slow, mind heat
Threading	all (wall thickness!)	better: heat-set inserts
Tumbling	small parts	series smoothing in media drum

4.3 Chemical & thermal smoothing

Method	Material	Effect	Safety
Acetone vapour	ABS, ASA	glossy, sealed surface	explosive! fume hood/outdoors only
Annealing	PLA, PA, PET	crystallinity↑, HDT↑, strength↑	warping possible, plan shrinkage

Part 5 · Finishing & Surface Quality

5.1 Surface metrics

Surface quality is described by roughness (Ra, Rz). FDM surfaces show a periodic waviness (layer lines) and a staircase effect on sloped faces depending on layer height and face angle.

Surface	Layer height	Ra (typ.)	Layer lines
FDM coarse	0.30 mm	Ra 20–35 µm	strongly visible
FDM standard	0.20 mm	Ra 10–25 µm	visible
FDM fine	0.12 mm	Ra 6–15 µm	faint
FDM ultrafine	0.08 mm	Ra 3–10 µm	barely
after smoothing/paint	—	Ra < 1–3 µm	not visible

5.2 Coating & functional finishing

- Priming (filler/primer): fills micro-grooves, promotes adhesion.
- Acrylic/2K paints: 2K-PUR for mechanically/chemically stressed surfaces.
- Electroplating/metallization: conductive paint + galvanic layer for metallic look/function.

Goal	Method	Effect
Tightness	epoxy impregnation, wall ↑	water/airtight
Wear protection	hard coat, PTFE coating	friction reduction
Conductivity	conductive paint, CF compound	ESD protection
UV protection	ASA choice, UV clear coat	outdoor durability

Part 6 · Defects & Remedies

Defect	Cause	Remedy
Warping	shrinkage, bed/room temp	heated bed, enclosure, brim/raft, ASA/ABS slow
Delamination (Z)	too cold/fast, draft	nozzle temp ↑, cooling ↓, enclosure
Stringing	oozing, moisture	retraction, drying, temp ↓
Elephant foot	first layer too hot/squished	Z-offset, cool first layer, bed temp ↓
Under-extrusion	clog, low flow	clean nozzle, flow ↑, temp ↑
Ghosting/ringing	resonance, acceleration	accel ↓, stiffer mechanics, input shaping
Dimensional deviation	flow, shrink, calibration	calibrate flow, compensate shrinkage

Part 7 · Application Classes & Material Choice

Application class	Example	Material	Verification depth
Decorative	figurines, vases	PLA, PLA-Silk	visual, dimension
Functional non-critical	holders, housings	PETG, ABS	visual, dimension, fit test
Technically loaded	gears, clamps	PETG-CF, PA-CF, PC	load verification, tensile test
Outdoor	signs, mounts	ASA, PC blend	UV/weather test
High temperature	near-motor, jigs	PC, PA, PPA	HDT verification, annealing
Flexible/damping	seals, buffers	TPU (shore choice)	hardness/function test

Process limits

No food contact without certified coating; layer grooves are bacterial reservoirs.
No use in safety-critical load paths without test verification (see SICHERHEITSWERK).
Application-specific regulation (medical, toy, automotive) requires its own conformity routes.

Reference

This engineering reference covers the materials and process side. Health, occupational and legal safety are described in the SICHERHEITSWERK compendium. Volume II covers the SLA/resin process.