FDM Polymers

A Technical Reference

Polymer chemistry, mechanical and thermal envelopes, calibration guidance, post-processing limits, and brand surveys for the polymer families that dominate engineering-grade FFF/FDM additive manufacturing.

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Hardware envelope	Prosumer FFF: nozzle to ~350 °C, bed to ~120 °C,
	chamber to ~65 °C, hardened nozzle (abrasive-rated)
Scope	Polyesters, polyolefins, polyamides, polycarbonate blends,
	styrenics, elastomers, high-performance specialty polymers
Reading level	Engineering practitioner; assumes FDM basics
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Preface

This volume is a single technical reference on the polymers used in engineering-grade FFF/FDM 3D printing, covering the commodity, engineering, and high-performance families a practitioner is likely to encounter. It uses one numbering scheme, one terminology set, and one bibliography throughout. Material common across polymer families - process physics, hardware tiers, and emissions safety - is consolidated into Part I (Foundations) and Part IX (Cross-cutting workflows) so it is stated once rather than repeated. The polymer-family-specific content is organized into Parts II-VIII, with each chapter following the same outline (chemistry → property envelope → brand landscape → print process → application fit → post-processing) where the underlying material supports it.

The polymer-family ordering follows the rough commodity-to-specialty axis that practitioners actually traverse: commodity polymers (PLA, PETG, PCTG) and styrenics (ABS, ASA, HIPS) first, then engineering polyolefins (PP), polyamides (aliphatic nylons and PPA), and polycarbonate blends, then the high-performance specialty tier (PPS, PSU/PPSU/PEI, PAEK), and finally the elastomer, support, and biodegradable niches. This is not a ranking by performance — it is a ranking by how a typical engineering build progresses from prototyping to functional service.

Three editorial principles apply throughout. First, data values are from manufacturer technical datasheets unless explicitly labeled otherwise; printed-specimen values are preferred to resin-pellet values where vendors disclose both, and resin-grade data points are flagged when used. **Second,** vendor marketing claims (especially around heat-resistance ceilings, food-contact compliance, and emissions) are reported as such and qualified where the empirical case is weak. **Third,** the author's own bench-measured calibration values for specific filament + nozzle combinations are included in Appendix B as worked examples on a representative prosumer setup — these are marked as measured rather than vendor-supplied and should be treated as starting points rather than universal values.

What this document is *not*: it is not a tutorial for FFF/FDM beginners, not a comprehensive print-failure troubleshooting guide, not a recommendation engine for specific projects, and not a substitute for per-spool calibration on the actual machine. Calibration values cited are starting points. Brand surveys reflect public TDS availability as of early 2026 and will go stale; the polymer-chemistry foundations and process-physics principles will not.

Two polymer families that are technically in scope receive less coverage than they merit. PPS (polyphenylene sulfide), available in CF-filled grades from Bambu, Polymaker Fiberon, and Flashforge, is summarized at the family level in Chapter 18 but does not have a dedicated brand survey. The PAEK family (PEEK, PEKK, PEKK-CF) is similarly summarized in Chapter 19. Both receive family-level coverage here rather than a dedicated brand survey.

Finally, three datasets and tools that inform this volume are referenced but not reproduced: a substantial body of independent third-party filament testing covering tensile, layer-adhesion, and thermal measurements; the author's published statistical analysis of community troubleshooting threads (~910 threads, 15-category classifier); and the author's calibration methodology published on Printables. These appear in Appendix D references where individual data points are drawn from them.

Part I

Foundations

Scope and methodology, polymer taxonomy, process physics that applies to every FDM polymer, hardware requirement tiers, and safety/emissions context — written once, referenced throughout.

1. Scope, methodology, and data caveats

Fused filament fabrication — referred to interchangeably as FFF or FDM — is overwhelmingly a thermoplastic process: a polymer is melted, extruded through a nozzle, and resolidifies as a welded bead bonded to the previous layer. Almost any thermoplastic that can be drawn into stable filament and re-melted within a printer's thermal envelope can be used; in practice, the commercial filament market clusters into nine polymer families covered in this volume.

1.1 Polymer families in scope

- **PLA:** the default commodity material; an aliphatic polyester (see Chapter 9 for why it is a family of its own).
- **Polyesters and copolyesters:** PETG, PET, PCTG, CPE, nGen, t-glase, AthenaX.
- **Styrenics:** ABS, ASA, HIPS.
- **Polyolefins:** PP and PE (unfilled, GF-reinforced, CF-reinforced).
- **Polyamides:** aliphatic nylons (PA6, PA66, PA12, PA612, PA11) and the PPA family.
- **Polycarbonate and PC blends:** PC/ABS, PC/PBT, PC-CF, PC-GF, PC-PTFE, ESD-PC, FR-PC.
- **Elastomers:** TPU, TPE, TPEE.
- **High-performance specialty:** PMMA, POM, PVDF, PPS, PSU, PPSU, PEI, PAEK (PEEK, PEKK).
- **Support and niche:** PVA, BVOH, PVB, PHA, PCL.

1.2 What is intentionally out of scope

Resin-based processes (SLA, DLP, LCD, MSLA), powder-bed processes (SLS, MJF, MJ), metal AM, and pellet-fed industrial FGF are not covered. The technical content here applies to the desktop and prosumer FFF/FDM hardware tier (typical maximum nozzle 350 °C, bed 120 °C, optional heated chamber to 65 °C). The ultra-high-temperature PAEK and PEI sections in Chapters 18–19 reach beyond this envelope and identify the hardware required.

1.3 Data hierarchy and citation discipline

Property data in this volume follow a strict source hierarchy. **Tier 1** is manufacturer technical datasheets (TDS) for filaments specifically (not pellet/resin), with printed-specimen values where the TDS explicitly identifies them. **Tier 2** is the resin manufacturer's TDS for the underlying base polymer (Eastman, BASF, Covestro, DuPont, Solvay), used when the filament TDS is silent on a property of interest and the filament is clearly built on that resin. Tier 3 is peer-reviewed literature and independent third-party testing of printed specimens. Where vendor marketing language conflicts with TDS values, the TDS wins; where TDS values conflict with independent testing, both are reported and the discrepancy noted.

1.4 Key caveats the reader should internalize

Anisotropy is structural. FFF parts are mechanically anisotropic. Reported tensile and impact strengths refer to XY-direction loading (the strongest direction) unless explicitly stated as Z-direction. Z-direction values are commonly 40–60% of XY for unfilled polymers, and 60–85% of XY for the toughest CF-reinforced grades. Engineering design that loads the print in Z without bracket testing on the actual machine is design by hope.

Resin TDS values overstate printed performance. A polymer's injection-molded tensile strength is typically 10–30% above the same polymer's FDM-printed tensile strength under good conditions, and a larger margin under typical conditions. The notched impact gap is wider: layer-bonded FDM parts can lose 50–70% of resin-grade notched Izod values. When a filament TDS quotes the resin value rather than a printed-coupon value, this is usually obvious from the cited test method (ISO 527 on “test bars” rather than printed specimens) and is flagged in the polymer chapters.

HDT, T_g, Vicat, and continuous-use temperature are not interchangeable. Heat deflection temperature (HDT) varies with load: HDT@0.45 MPa is a generous marketing-friendly number, HDT@1.8 MPa is closer to engineering reality. Vicat softening temperature reports a different phenomenon entirely (needle penetration). Glass transition (T_g) and melting point (T_m) are the polymer-physics anchors. For amorphous polymers (PETG, PCTG, ABS, ASA, PC), service temperature is bounded by T_g - parts will creep under sustained load above it. For semi-crystalline polymers (PA, PP, PE, PPS, PEEK), crystallinity governs the actual heat performance, and a printed part with low crystallinity will deform far below the resin's HDT.

Moisture is a first-order variable. Polyamides, soluble supports, PCTG-CF, PP-GF (despite the polymer being non-hygroscopic), and most high-performance polymers all lose print quality and mechanical performance when wet. Active drying is hardware, not optional convenience. The polymer chapters identify which materials are forgiving (PLA, PP, PCTG unfilled) and which are not (PA6, PVA, PEI, PEEK).

Brand-to-brand variance within a single polymer class. “PETG” from one vendor and “PETG” from another are not the same material in any rigorous sense — they share a backbone family, but additive packages, impact modifiers, colorants, and base resin grade vary enough to shift tensile strength by 20%, elongation by 100%, and printability significantly. The brand surveys in each chapter document these variations where vendor TDS data supports it.

2. FDM polymer taxonomy and the labeling problem

Filament marketing names are not chemistry. Three persistent confusions dominate the FDM materials landscape and create the most reliable source of bad purchasing decisions.

2.1 The PETG / PCTG / PCT continuum

All three are terephthalate copolyesters built from terephthalic acid (TPA) plus a glycol mix. The dominant glycol determines the name. With 1,4-cyclohexanedimethanol (CHDM) less than 50 mol% of the diol fraction the polymer is PETG; with CHDM above 50 mol% it is PCTG; pure TPA + CHDM with no ethylene glycol gives PCT, a semi-crystalline polyester with a 285 °C melting point that is impractical for desktop FDM. Eastman Tritan, marketed as a polycarbonate substitute, is technically a terpolymer of TPA + CHDM + tetramethyl-cyclobutanediol (TMCD); filament marketed as “PCTG” built on Tritan resin is chemically distinct from generic CHDM-rich copolyester “PCTG” even though both wear the same three letters.

2.2 PP, PPA, PPS — three unrelated families sharing initials

PP (polypropylene) is a polyolefin commodity plastic, T_g below room temperature, T_m near 160 °C, Shore D around 70, hydrophobic, low surface energy. **PPA** (polyphthalamide) is a semi-aromatic polyamide — a nylon with phthalic acid in the backbone — T_g 120–140 °C, T_m 290–320 °C, hygroscopic. **PPS** (polyphenylene sulfide) is an aromatic engineering polymer with near-universal chemical resistance and continuous-use temperatures above 200 °C. The polymers, processing windows, hardware requirements, mechanical properties, and applications have essentially nothing in common; only the leading letters coincide.

2.3 The PAHT / HTN / PPA mess

“PAHT” (Polyamide High-Temperature) is a marketing category, not a chemistry. It originally referred to PPA-based filaments around 2020–2022 but has been applied to modified PA6, modified PA12, and PA6/66 copolymers. Siraya Tech Fibreheart PAHT (pre-2024) was true PPA chemistry and was rebranded to Fibreheart PPA in late 2024; Bambu Lab PAHT-CF is PA12-based, not PPA; BCN3D PAHT CF15 is an unspecified high-temperature PA blend; Qidi labels theirs “PAHT (PPA)” on the packaging itself, acknowledging the chemistry. “HTN” (High-Temperature Nylon), used by 3DXTech for the CarbonX HTN+CF product line, is functionally synonymous with PPA at the chemistry level. The result is that filaments labeled PAHT, HTN, PA-HT, and PPA span four different base polymers; the technical datasheet, not the product name, is the only reliable identifier.

2.4 “PC” is almost always an alloy or composite

Pure unmodified polycarbonate is rare in commercial filament. The PC market in FDM divides into **polymer alloys** (PC blended with another polymer to reduce warping or shift mechanical balance — most commonly PC/ABS or PC/PBT) and **PC composites** (PC compounded with carbon fiber, glass fiber, PTFE, conductive additives, or flame-retardant packages). When a filament is sold as “PC,” the TDS will typically reveal it as one of these — and the property envelope, processing window, and printability all depend on which alloying or compounding strategy was used. Prusament PC Blend, Bambu PC, and PolyMax PC are the most well-documented “general-purpose PC” products and are all alloys with undisclosed partner polymers.

2.5 Filler designations and content disclosure

Carbon-fiber and glass-fiber reinforcement levels are usually quoted as weight percent but are rarely confirmed: a “PC-CF” spool may contain anywhere from 10% to 25% chopped carbon fiber, and the mechanical envelope shifts substantially across that range. Spectrum, Prusament, Fiberlogy, 3DXTech, and Polymaker typically disclose the fiber loading (e.g., Spectrum PCTG-CF10 means 10% CF; Polymaker PA6-CF20 means 20% CF). Bambu and several Asian-market brands do not disclose. When the loading is undisclosed, the practical rule is that printed-specimen modulus values in the range of 5–7 GPa indicate roughly 15–20% CF; modulus above 9 GPa indicates 20% or higher CF; modulus below 4 GPa indicates less than 15% CF (or significant fiber breakage during compounding).

3. Process physics common to all FDM polymers

Every FDM print encounters the same handful of underlying physics problems regardless of polymer family. Understanding them once makes the polymer-specific chapters readable as variations on shared themes rather than five disconnected sets of rules.

3.1 Interlayer welding and anisotropy

Layer-to-layer bonding in FDM is driven by polymer chain inter-diffusion across the boundary between an extruded bead and the previously-deposited bead beneath it. The diffusion process requires temperatures above the polymer's glass transition (for amorphous polymers) or near/above the melting point (for semi-crystalline polymers), sufficient time before the interface cools below those thresholds, and adequate pressure (controlled by extrusion multiplier and line width).

The result: parts are mechanically anisotropic. XY tensile strength (load applied parallel to the build plate) is the strongest direction. Z tensile strength (load applied perpendicular to the layers) is dominated by the interlayer weld quality and is consistently lower. For unfilled low-crystallinity prints like PLA and PETG with good print conditions, Z is 60–85% of XY. For fiber-filled polymers, the gap widens because the fibers align in the print direction and contribute nothing to Z strength: Z values can be 40–60% of XY for PA6-CF or PPA-CF. For high-temperature semi-crystalline polymers like PEEK printed below the chamber temperature required for full crystallization, Z strength can drop below 30% of XY.

Practical implications: design load-bearing parts so the principal stress aligns with XY; increase wall count (3–5 perimeters rather than the typical 2) to compensate for interlayer weakness in walls; raise print temperature toward the upper end of the polymer's recommended range for parts that load Z; reduce or eliminate part cooling for polymers where layer adhesion is marginal (PP, PC, PEEK, PPS); when in doubt, bracket-test the actual loading geometry.

3.2 Warp: crystallization shrinkage vs thermal contraction

Warping has two distinct mechanisms that get conflated. **Thermal contraction** happens to every polymer as it cools from melt to room temperature; the dimensional change is small (0.4–1% for amorphous polymers) and reversible if the part is heated again. **Crystallization shrinkage** happens only in semi-crystalline polymers (PP, PE, PA, PPS, PEEK) as ordered crystalline regions form during cooling; it is irreversible (the polymer chains lock in place) and the volumetric change is large — 1.5–2.5% for polypropylene, 2–3% for some nylons. When this shrinkage is accumulated layer-by-layer in an FFF print, the in-plane component pulls inward on every layer and concentrates stress at the part edges.

This explains why amorphous polymers (ABS, PC, ASA) warp from thermal contraction alone — their absolute shrinkage is modest but the stress concentrates over large flat areas — while semi-crystalline polymers (PP, PA) warp far more aggressively for any given part size. It also explains why fiber reinforcement reduces warp so effectively: glass and carbon fibers do not crystallize, do not shrink thermally to the same degree, and physically constrain matrix shrinkage. A 30% glass-loaded PP exhibits roughly one-third the linear shrinkage of unfilled PP in the print direction; the warp tendency is correspondingly reduced from “effectively unprintable on parts larger than a few centimeters” to “routinely printable on a 250 mm bed.”

3.3 Bed adhesion as an interfacial chemistry problem

Bed adhesion is, fundamentally, wetting and intermolecular attraction between the molten first-layer polymer and the build surface. Polar polymers (PLA, PETG, PCTG, ABS, PC, PA) present hydrogen-bond acceptors and dipoles that can form interactions with polar build surfaces — PEI (polyetherimide, surface energy ~40 mN/m) is the dominant build surface because it grips this entire family. Glass and powder-coated steel work via similar polar mechanisms with somewhat lower energy.

Non-polar polymers — polypropylene above all others, with surface energy around 30 mN/m — cannot present polar groups for those interactions. PEI, glass, mirror, and powder-coated steel all fail to grip PP regardless of bed temperature. The practical solutions reduce to the same principle: place a polypropylene-compatible surface on the bed and let PP-on-PP self-adhesion carry the print. This is why printer manufacturers and the broader PP community converged on dedicated PP-coated print sheets, PP packing tape, and PP-specific adhesives (Magigoo PP). See Chapter 24 for the consolidated by-family adhesion guide.

3.4 Moisture: which polymers care and why

Polymer moisture sensitivity in FDM has two distinct consequences: print-quality degradation (stringing, oozing, surface roughness, bubbling, micro-voids in the bead) and mechanical property degradation (loss of stiffness as water plasticizes amide bonds in polyamides; hydrolytic chain scission in some polyesters at elevated temperature).

Highly hygroscopic (active drying mandatory): PA6 (saturated absorption 8–10%), PVA and BVOH (soluble supports — both are hydrophilic by design), PEI (1.25% nominal, but the parts of interest are printed near 400 °C and any moisture flashes catastrophically), PEEK and PEKK (low absolute uptake but extreme print temperatures amplify any moisture).

Moderately hygroscopic (drying strongly recommended before serious prints): PA12 (saturated ~1.5%), PA612 (~3%), PPA (~2.5%; less than PA6 but still problematic), PCTG and PETG (0.1–0.4%; cosmetic effect on optical-clarity prints, modest mechanical effect), PC and PC blends (0.3–0.5%), most TPU formulations.

Not hygroscopic (drying generally unnecessary): polypropylene (saturated <0.05%), polyethylene, PVDF, PPS, PLA in normal storage conditions (PLA can pick up enough moisture over months in humid storage to cause cosmetic issues, but mechanical performance is largely unaffected).

3.5 Drying protocols

Polymer family	Temp (°C)	Time (h)	Notes
PLA	45–55	4–6	Rarely required; only after months in humid storage
PETG, PCTG	60–70	4–6	Required for transparent or optical-clarity prints
ABS, ASA, HIPS	60–70	4–6	Rarely critical but improves first-layer quality
TPU, TPE	50–65	4–6	Softer grades (60A–80A) use the lower end; do not exceed Vicat
PA12, PA612	70–80	8–12	Mandatory before every serious print
PA6, PA66	80–90	10–16	Mandatory; spool can deform above 90 °C
PPA, PPA-CF, PPA-GF	100–140	8–12	Convection oven preferred; do not exceed 160 °C
PC, PC blends	80–100	6–8	Stringing is the most common moisture symptom
PC-CF, PC-GF	90–110	8–10	Fiber loading increases moisture pickup rate and capacity
PVA, BVOH	45–60	8–12	Hygroscopic by design; print directly from a dryer
PEI (ULTEM-class)	130–150	4–6	Industrial-grade dryer required at these temperatures
PEEK, PEKK	120–130	≥4	Convection oven required; in-chamber drying generally inadequate
PP, PE	(not required)	—	Saturated absorption <0.05%; drying offers no benefit

Table 3.1 — Drying protocols by polymer family. Source: manufacturer TDS values; PEEK/PEKK row reflects general guidance for high-temperature polymer printing. Conservative protocol for engineering work: dry before every print; for prototyping and casual use, follow the "rarely required" exceptions only when filament has been in low-humidity storage.

3.6 Crystallinity and annealing

For amorphous polymers, annealing relieves residual stress but does not change crystallinity (there is none). Practical gains are modest: a small reduction in long-term creep, slight improvement in dimensional stability, no meaningful HDT shift. Annealing temperature must stay below T_g to avoid distortion; for PCTG the safe range is 60–70 °C for 2–4 hours.

For semi-crystalline polymers, annealing is a fundamentally different operation. The FDM process cools rapidly enough that crystallinity is incomplete; post-print heat treatment above T_g but below T_m allows further crystallization, which dramatically improves HDT and stiffness. PLA is the canonical example: annealing PLA at 90–110 °C for 1–2 hours can shift HDT from ~55 °C to about 120 °C by raising crystallinity from below 5% to above 30%. The cost is dimensional change (shrinkage during crystallization, typically 1–3%) and warp risk for thin walls. PA, PP, and PEEK respond similarly; PPA's specific annealing schedules are detailed in Chapter 14. **Unfilled PPA is the notable exception**: Siraya explicitly advises against annealing it because the as-printed warp tendency carries through the heat soak; anneal the CF and GF variants instead.

4. Hardware requirement tiers

FDM printer capability defines which polymer families are accessible. Four practical hardware tiers, mapped to the polymer families this volume covers:

Tier	Capability envelope	Accessible polymers	Distinguishing features
1 — Baseline desktop	Nozzle ≤250 °C, bed ≤100 °C, open or passive enclosure	PLA, PETG, PCTG, HIPS, soft TPU, PVA, BVOH, PVB, PHA, basic PP	Brass nozzle, single-extruder, no chamber heat; entry-level price tier
2 — Engineering desktop	Nozzle 260–300 °C, bed 100–120 °C, enclosed, no active chamber	Plus ABS, ASA, PA12, PA612, PC blends, PP-GF, PP-CF, ESD-PC, PVDF	Enclosed CoreXY or bedslinger with hardened-nozzle support and 250+ °C hotend
3 — Engineering with active chamber	Nozzle to 350 °C, bed to 120 °C, active chamber to 65 °C, hardened/abrasive nozzles standard	Plus PA6, PA6-CF, PA66, PPA, PPA-CF, PPA-GF, PC-CF, PC-GF, PPS-CF	Thermostat-controlled chamber, sealed enclosure, integrated filament drying; upper bound of the prosumer envelope
4 — Ultra-high-temperature industrial	Nozzle 380–450 °C, bed 140–155 °C, chamber ≥85 °C, controlled atmosphere	Plus PEEK, PEEK-CF, PEKK, PEKK-CF, PEI/ULTEM, PSU, PPSU, PPS unfilled	Industrial-class: high-temp hotend, actively-controlled enclosure, vendor-supplied profiles

Table 4.1 — Hardware capability tiers and polymer accessibility. Tier crossings are not discrete: Tier 2 hardware will run Tier 3 materials with degraded reliability for small parts; Tier 3 hardware will run Tier 4 materials only on small parts with careful chamber management.

4.1 Nozzle materials by polymer

- **Brass:** the default - fine for unfilled PLA, PETG, PCTG, ABS, ASA, HIPS, PC blends, unfilled nylons, and TPU; wears too fast for any fiber-filled material.
- **Hardened steel:** the practical minimum for any CF- or GF-reinforced filament; lasts hundreds of hours on typical CF loadings.
- **Ruby and tungsten carbide:** extend life on heavy fiber loadings (PA-CF, PPA-CF, PPS-CF, PEEK-CF) and on metal-filled or ESD-conductive filaments.
- **Polycrystalline diamond (PCD):** the E3D Diamondback family, the most wear-resistant option available and the consensus choice for fiber-filled production work. PCD tips are non-conductive, so inductive nozzle-offset sensors cannot detect them - camera-based offset calibration is required.
- **Obxidian:** hardened steel with an embedded nano-coating; sits between hardened steel and PCD on the wear/cost curve.

4.2 Build surface ecosystems

- **Smooth PEI:** the spring-steel plate ubiquitous on prosumer hardware; grips PLA, PETG, PCTG, ABS, ASA, PC, PA12, PA612, and most TPUs without adhesives.
- **Textured PEI:** the powder-coated variant; grips the same materials with slightly lower force, eases part removal, and is preferred for production work.
- **Glass:** the universal low-friction surface; works for materials that bond via an adhesive layer (packing tape, Magigoo, glue stick) rather than chemical affinity.
- **G10 garolite:** preferred for high-warp nylons and long PC Blend prints, where PEI grip can damage the plate or the part.
- **Dedicated PP sheets:** the most reproducible option for polypropylene and best for large PP prints; smaller PP parts also adhere with PP packing tape or Magigoo PP.

4.3 Enclosure and chamber strategy

A passive enclosure (just walls and a top) raises ambient air temperature around the print to roughly 40–50 °C and reduces convective heat loss; sufficient for ABS, ASA, PC blends, unfilled nylons, and most everything in Tier 2. An active heated chamber (thermostatically controlled heating element) is required for PPA, PPS, PEEK, PEKK, and PEI because their print-process temperature windows are narrow enough that even passive convection drops the upper-layer temperature below crystallization onset, ruining layer adhesion.

Active chamber temperature is itself a constraint on filament storage in multi-material buffer systems: moisture-sensitive filaments in a chamber above 45 °C will dry passively but other filaments in the same enclosure may soften (TPU, PLA), and spool deformation can occur in extreme cases. Newer thermally-isolated buffer systems separate the storage compartment from the printer enclosure to mitigate this.

5. Safety, emissions, and sustainability

FDM printing emits ultrafine particles (UFPs) and volatile organic compounds (VOCs). The magnitudes and chemical identities vary by polymer, additive package, and nozzle temperature. This chapter is the consolidated safety discussion; the polymer-specific chapters reference back here rather than repeating the framework.

5.1 What the literature actually shows

Multiple peer-reviewed studies and government guidance documents (NIOSH 2024-103, ANSI/CAN/UL 2904, EPA studies) converge on a few robust findings. **UFP emission rates rise sharply with nozzle temperature**; PEEK and PEI printing at 400+ °C produces orders of magnitude more particles than PLA at 210 °C. **ABS emits styrene** as a prominent VOC; this is the most consistent VOC association in the literature. **Filled and additive-heavy filaments shift the emission profile**: CNT-filled ESD grades, flame-retardant compounds, and metal-filled aesthetic filaments produce different particle chemistries than the base polymer. **Source control beats dilution**: a ventilated enclosure with local exhaust reduces room particle concentrations by 99% in NIOSH measurements; raising the room HVAC rate produces much smaller reductions.

5.2 Practical engineering controls

Enclosure with active exhaust is the most effective control for Tier 3 and Tier 4 polymer printing. Many modern enclosed printers include HEPA plus activated-carbon filtration as part of the chamber cycle; this is necessary but not sufficient for the highest-emission materials. Vent the enclosure exhaust to outdoors for PEEK, PEI, PEKK, and PPS work.

Material-specific timing: high-emission materials should be printed during off-hours in occupied spaces; the post-print filtration cycle (a feature of most enclosed printers) is most valuable in the 5–15 minutes after extrusion stops, when chamber concentrations are highest. A material-conditional Start/End G-code template can hold the filtration cycle for longer durations on the higher-emission materials (typical values: 180 s for ABS/ASA/PA/PPA-CF, 300 s for PC, none for PLA/PETG/PCTG/standard TPU) — see Appendix B for the worked-example template.

5.3 Material-specific hazards

POM/acetal can release formaldehyde when overheated; multiple SDS documents specifically warn of heavy formaldehyde fuming above 230 °C, and POM should be printed only with active ventilation. **Polypropylene combustion** in failed prints produces standard hydrocarbon combustion products (CO, CO_2, water); not uniquely hazardous but a normal fire risk in an enclosed printer. **PC pyrolysis** can produce phenol-like compounds with characteristic odor; if you smell phenol while printing PC, the nozzle is overheated. **Fluoropolymers** (PVDF, PTFE-filled PC) can release hydrogen fluoride at extreme temperatures (≥315 °C for PVDF; PTFE itself decomposes above 350 °C); avoid running PTFE tubing in hotend zones for filaments processed above 280 °C.

Solvent post-processing introduces a separate hazard class. Acetone (used for ABS, ASA, HIPS smoothing) is highly flammable with a low flash point; limonene (HIPS dissolution) is a skin sensitizer; dichloromethane (PCTG and PC dissolution) is toxic and an OSHA-regulated carcinogen. Treat solvent post-processing as a chemical handling operation: PPE, ventilation, ignition source control, secondary containment.

5.4 End-of-life and recyclability

“Recyclable thermoplastic” in chemistry does not mean “recycled in practice.” PLA carries a credible composting story under industrial conditions; PETG and PCTG are polyester (resin code 7 in most jurisdictions) and are theoretically recyclable but curbside infrastructure rarely accepts them. ABS and PC are technically recyclable but practically downcycled. Filled grades (CF, GF, FR, ESD) are essentially non-recyclable because the additives prevent clean melt reprocessing.

Vendors with active recycled-content programs: 3D-Fuel ReFuel (regrind PCTG, mechanical envelope indistinguishable from virgin), Fiberlogy R PP (100% post-consumer/post-industrial PP), Braskem FL900PP-CF (100% recycled CF feedstock), Polymaker PolyTerra PLA (carbon-offset PLA with paper spool), Fishy Filaments / Fillamentum Porthcurno (ocean-recovered PP-GF). These are real progress; treat them as marginal improvements over virgin material rather than as license to print recklessly.

Part II

PLA Family

The PLA family - the most-printed material in FDM and the natural starting point.
Easy to print, biodegradable in principle, and the reference against which every other polymer's printability is judged.

6. PLA family

PLA (polylactic acid) is the most-produced biopolymer and the most-consumed FDM filament by volume. Sourced from corn-derived lactic acid, it processes at the lowest temperature and pressure of any commercial filament, prints reliably without an enclosure, and exhibits the lowest emission profile of any polymer family. The conventional “not strong” criticism of PLA misreads the material: PLA exceeds PETG on tensile strength and modulus and matches ABS on most non-impact metrics. The actual weaknesses are thermal (T_g 55–65 °C) and notch sensitivity, not bulk tensile.

6.1 PLA variants in the commercial market

Standard PLA is the base polymer; tensile strength 50–70 MPa, elongation 3–8%, brittle in notch loading. **PLA+ / Tough PLA / PolyMax PLA** blends impact modifiers (typically a flexible polymer phase or rubber) to raise notched impact at the cost of 10–20% tensile strength. **HTPLA (high-temperature PLA)** includes nucleating agents to accelerate crystallization; the as-printed part is weak but annealing raises crystallinity from <5% to 30%+, shifting HDT from ~55 °C to ~120 °C. **LW-PLA (lightweight PLA)** contains chemical foaming agents that activate at elevated nozzle temperatures, producing a part with 30–50% density reduction; standard in RC aircraft. **PLA/PHA blends** (colorFabb, Fillamentum) combine PLA with polyhydroxyalkanoate for biodegradability and improved layer adhesion. **Filled PLAs** (wood, metal, glow, carbon, glass) are PLA matrix with cosmetic or modest functional additives.

6.2 Property envelope

Property	Standard PLA	PLA+ / Tough	HTPLA (annealed)	LW-PLA (foamed)
Density (g/cm^3)	1.24	1.20–1.24	1.24	0.6–0.9
T_m (°C)	150–170	150–170	150–170	150–170
T_g (°C)	55–65	55–65	55–65 (post-anneal effective HDT ~120	55–65
Tensile strength (MPa)	50–70	40–60	60–70	20–35
Tensile modulus (GPa)	3–4	2–3	3–4	1–2
Elongation @ break (%)	3–8	10–25	3–6	5–10
Notched Izod (kJ/m^2)	2–4	6–12	2–4	low
Nozzle (°C)	200–220	210–230	210–230	220–260*
Bed (°C)	50–60	50–60	50–60	50–60

*Table 6.1 — PLA family property envelope. *LW-PLA nozzle temperature is the foaming-control variable: 220 °C gives near-solid extrusion; 250 °C+ activates full foaming. Per-spool calibration of foaming temperature is mandatory.*

6.3 Process and calibration

PLA prints on essentially any FDM hardware with minimal tuning. Nozzle 200–220 °C, bed 50–60 °C, fan 100% after layer 2 or 3, brass nozzle adequate for unfilled grades. Glue stick or hairspray on glass for adhesion; smooth PEI grips without adhesives. Wood-filled, metal-filled, and glow-in-the-dark PLA require hardened nozzles; LW-PLA tolerates brass for typical run times because foaming reduces solid contact with the nozzle bore.

Calibration order matches the generic FDM workflow: temperature tower 190–220 °C in 5 °C steps, max volumetric flow (typically 12–18 mm^3/s on standard hotends, up to 30 mm^3/s on high-flow setups like CHT or Bambu HF), extrusion multiplier via single-wall cube, pressure advance bracket (0.020–0.040 typical), XY shrinkage compensation (0.3% standard). PLA is the calibration baseline for most printers.

6.4 Application fit

PLA earns its dominant market share by being the right choice for prototyping, display models, RC aircraft (LW-PLA), educational and consumer 3D printing, and cosmetic parts that do not see service above 50 °C. It is *not* the right choice for parts that see summer car interiors (above 70 °C inside; PLA creeps), repeated impact loading (brittle), outdoor service of any duration (UV and humidity both degrade unannealed PLA), or parts under sustained mechanical load. Annealed HTPLA broadens the temperature window but does not fix the impact problem.

Part III

Polyester Family

The polyester family in FDM: PETG and PCTG, the glycol-modified copolyesters that dominate functional printing, and PET with its reinforced PET-CF and PET-GF grades.

7. PETG and the copolyester family

PETG (polyethylene terephthalate glycol-modified) is the workhorse functional filament: easier to print than ABS, tougher than PLA, chemically resistant to a wider range of solvents than either, and available from essentially every filament manufacturer at $15–25/kg. The copolyester family extends beyond strict PETG into marketed-as-CPE, nGen, AthenaX, and t-glase variants · all chemically related, all amorphous, all CHDM-containing.

7.1 Chemistry

PETG is polyethylene terephthalate (PET) with a fraction of the ethylene glycol replaced by 1,4-cyclohexanedimethanol (CHDM). When CHDM is less than 50 mol% of the diol fraction, the polymer is called PETG; the CHDM disrupts crystalline packing enough to keep the polymer amorphous (no melt-driven crystallization, no Schlieren texture, full optical transparency in clear grades) while leaving the PET-class tensile envelope intact. Eastman Amphora and Eastman Eastar are the dominant base resins; SK Skygreen and Chinese-sourced PETG-equivalents fill the lower price tier.

7.2 Property envelope

Property	Typical PETG	Notes
Density (g/cm^3)	1.23–1.27	Pigment-dependent
T_g (°C)	75–80	Service ceiling without anneal
T_m (°C)	n/a	No true T_m - amorphous; print 230-250
HDT @ 0.45 MPa (°C)	70–75	Filament-form value
Tensile strength @ yield (MPa)	40–50	ISO 527, XY
Tensile modulus (GPa)	1.9–2.1	
Elongation @ break (%)	8–25	Brand-dependent; tough grades higher
Notched Izod (kJ/m^2)	4–8	About 2× PLA
Saturated moisture absorption (%)	0.2–0.4	Cosmetic effect on prints
Optical clarity	good	Clear grades 85–90% transmittance
UV stability	moderate	Months outdoor; pigments help

Table 7.1 — PETG typical property envelope. Brand-to-brand variation is approximately ±15% on tensile and ±50% on elongation.

7.3 Process parameters

Nozzle 230–250 °C (some impact-modified grades up to 260 °C), bed 80–90 °C, part cooling 30–60% (lower than PLA, higher than ABS), brim recommended for parts over 60 mm in longest dimension. Pressure advance bracket typically 0.030–0.060. Max volumetric flow 10–14 mm^3/s on standard hotends. PETG is sticky in melt and tends to over-adhere to smooth PEI: glue stick on glass, or PVP coating, or accept reduced bed temperature on textured PEI to prevent sheet damage on part removal.

7.4 Variants and the broader copolyester family

Tough PETG / PETG+ / co-PETG: impact-modified grades from Polymaker (PolyMax PETG), Fiberlogy, and others; elongation pushed to 100%+ at modest tensile sacrifice. PolyMax PETG in particular is high-CHDM PETG and approaches PCTG behavior without being labeled as such. nGen, CPE, CPE+, **Amphora-based**: Eastman Amphora copolyester grades marketed under various proprietary names; functionally similar to PETG with slightly higher T_g and toughness. t-glase, PETT Taulman's high-clarity copolyester; sold as “100% recyclable” though local infrastructure rarely supports it. **AthenaX** (FormFutura): positioned in the FormFutura X-line as a step above ApolloX (ASA) and TitanX (ABS); chemistry not disclosed but property envelope is PCTG-class.

7.5 Application fit

PETG is the right choice for: functional prototypes that need toughness PLA lacks, parts that see occasional bumps but not sustained impact, transparent enclosures (in clear grades), indoor mechanical parts that see service up to 60 °C, parts requiring food-contact compatibility at the resin level (not the printed surface). It is *not* the right choice for: parts that see repeated drops or impact loading (use PCTG or PC blend), parts above 70 °C service (T_g ceiling), outdoor UV exposure exceeding a few months (use ASA), or precision-fit assemblies where the higher moisture sensitivity and shrinkage variability matter.

8. PCTG — deep dive

PCTG occupies a useful niche between PETG and PC. The headline mechanical signature is an order-of-magnitude improvement in notched impact strength over PETG — typical Izod values of 8-24 kJ/m² vs PETG's 4-8 kJ/m² while sharing the same processing envelope. Where PETG loses energy to crack propagation, PCTG absorbs it in plastic deformation. The cost is a $10–15/kg premium over PETG and (more importantly) the fact that not every spool marketed as "PCTG" uses the same base resin.

8.1 Polymer chemistry: CHDM, TMCD, and the Tritan caveat

PCTG is built on the same TPA + glycol-mix backbone as PETG, but with CHDM above 50 mol% of the diol fraction. The dominant CHDM raises T_g modestly (85–95 °C vs PETG's 75–80), eliminates crystallinity completely (full transparency, no Schlieren scattering), and produces the notched-impact toughness step-up. Three monomers define the compositional space:

Monomer	Role in the polymer	Effect when dominant
Terephthalic acid (TPA)	Aromatic diacid backbone	Stiffness, UV absorption, hydrolytic anchor
Ethylene glycol (EG)	Linear short diol	Promotes crystallinity; PET-like packing
1,4-cyclohexanedimethanol (CHDM)	Bulky cycloaliphatic diol	Disrupts crystallinity; raises T_g and toughness
2,2,4,4-tetramethyl-1,3-cyclobutanediol (TMCD)	Rigid cyclic diol; Tritan-specific	Further raises T_g; improves hydrolytic stability

Table 8.1 — The compositional building blocks of the PETG–PCTG–Tritan family.

Eastman Tritan (the resin behind most premium "PCTG" filaments) is technically a terpolymer of TPA + CHDM + TMCD — not strictly PCTG. The TMCD ring lifts T_g and hydrolytic stability beyond what TPA + CHDM alone produces, which is why Eastman markets Tritan as a polycarbonate substitute in dishware applications. Filaments built on Tritan-class resins (3D-Fuel Pro PCTG, Essentium PCTG, some Spectrum and Fiberlogy grades) should be expected to outperform pure TPA-CHDM PCTG on the temperature and hydrolysis axes; the converse is that not every filament sold as "PCTG" is the same polymer. The filament TDS rarely identifies the underlying resin grade.

8.2 Reference property envelope: Eastman Tritan TX1001 (resin)

The values below are from the Eastman TX1001 TDS. These are test-bar values, not printed-part values; printed mechanical envelope runs 10–30% below the tensile and modulus numbers here, with notched Izod the most sensitive to layer-bonding quality.

Property	Method	Value
Specific gravity	ASTM D792	1.18
Tensile stress @ yield (MPa)	ISO 527	43
Tensile strength @ break (MPa)	ISO 527	58

Property	Method	Value
Elongation @ break (%)	ISO 527	185
Tensile modulus (MPa)	ISO 527	1,548
Flexural modulus (MPa)	ISO 178	1,495
Flexural strength (MPa)	ISO 178	59
Izod, notched @ 23 °C (kJ/m^2)	ISO 180	93
Izod, notched @ −40 °C (kJ/m^2)	ISO 180	20
Rockwell hardness (R scale)	ASTM D785	112
Total light transmittance (%)	ASTM D1003	90
Haze (%)	ASTM D1003	<1
HDT @ 0.455 MPa (°C)	ASTM D648	99
HDT @ 1.82 MPa (°C)	ASTM D648	85
Mold shrinkage (in/in)	ASTM D955	0.005–0.007
Drying schedule	—	88 °C, 4–6 h
Melt processing range (°C)	—	260–282

Table 8.2 — Eastman Tritan TX1001 resin TDS. Note the gap between resin HDT (99 °C) and typical filament HDT (~76 °C) — characteristic of additive packages that prioritize printability over peak heat performance.

8.3 Filament-form property envelope (representative brands)

Property	Spectrum Premium	Fiberlogy PCTG	FormFutura AthenaX	Tritan TX1001 (resin)
Density (g/cm^3)	1.23	~1.23	~1.23	1.18
Tensile @ yield (MPa)	44	—	44	43
Tensile @ break (MPa)	46	—	44	58
Elongation @ break (%)	220	—	220	185
Flexural strength (MPa)	60	—	—	59
Flexural modulus (MPa)	1,600	—	—	1,495
Notched Izod (kJ/m^2) *	93	~90	—	93
HDT @ 0.455 MPa (°C)	76	76	—	99
HDT @ 1.82 MPa (°C)	64	—	—	85
Vicat softening (°C)	88	—	—	—
Rockwell R hardness	105	—	—	112

*Table 8.3 — PCTG filament property envelope by brand. Dashes indicate values not published. The filament-vs-resin HDT gap is consistent with Z-axis weakness of FDM parts plus printability-tuned additive packages. * Notched-Izod figures are resin-basis TDS values; printed PCTG specimens run far lower — see the printed envelope in §8.2.*

8.4 Chemical and environmental resistance

PCTG is moderately polar and resistant to most non-polar solvents, dilute mineral acids, salt solutions, and aliphatic oils. It is attacked by strong bases, concentrated mineral acids, ketones (acetone, MEK), chlorinated solvents (DCM, chloroform), and many aromatic solvents (toluene, xylene). The CHDM/TMCD-rich backbone gives PCTG a real step up over PETG against acids, alcohols, and detergents — 3D-Fuel publishes chemical-resistance ratio (CRR) data claiming 1.5–2× PCTG advantage over PETG across most cleaner and oil exposures.

Class	Examples	PCTG behavior
Mineral acids, dilute	10% HCl, 10% H_2SO_4	Resistant; no swelling at RT
Mineral acids, conc.	Conc. HCl, HNO_3, H_2SO_4	Attacked; ester hydrolysis at elevated T
Strong bases	NaOH, KOH	Slow saponification; avoid chronic exposure
Aliphatic hydrocarbons	Hexane, mineral oil, kerosene	Resistant
Alcohols	IPA, ethanol, methanol	Resistant; cosmetic crazing under load
Ketones	Acetone, MEK	Attacked; softening, crazing, dissolution
Esters	Ethyl acetate, butyl acetate	Attacked; not useful for vapor smoothing
Chlorinated solvents	DCM, chloroform, TCE	Strongly attacked; lab handling only
Aromatic solvents	Toluene, xylene	Attacked; surface softening
Aqueous detergents	Dishwasher cycles	Excellent (Tritan target application)
Fuels	Gasoline, diesel	Marginal; both PETG/PCTG swell over time
UV exposure	Outdoor sun	Better than PLA/PETG; pigment-dependent

Table 8.4 — PCTG chemical compatibility. Tritan-class grades carry hydrolytic-stability marketing claims supported by Eastman's dishwasher test data.

8.5 Brand landscape

Brand	Product	$/kg	Notable
3D-Fuel	Pro PCTG	~30	Tritan-based; broad colors; ReFuel (regrind) variant
Spectrum	Premium PCTG	~25	Well-documented TDS; full CF and GF variants
Fiberlogy	PCTG	~30	Pure TR (food-contact) clear; CF and GF variants
FormFutura	AthenaX	~30	Positioned in X-line alongside ApolloX (ASA), TitanX (ABS)
Essentium / Vision Miner	PCTG	~45	US; commonly built on Tritan TX1001
American Filament	PCTG	~25	US; food-contact clear and basic colors
Nobufil	PCTG	~30	Austrian; smaller catalog; color-focused
Tangled Filament	PCTG (preorder)	~22	Aggressive price target ($13/kg eventual)
Polymaker	PolyMax PETG	~22	*Marketed as PETG;* chemically high-CHDM PETG, near PCTG

Table 8.5 — PCTG brand landscape (early 2026). Prices are typical 1 kg / 1.75 mm retail, expect ±15% drift. Polymaker PolyMax PETG is included because Polymaker's wiki identifies it as high-CHDM PETG, which puts it chemically adjacent to

PCTG; nominally still PETG.

8.6 Reinforced and specialty grades

PCTG-CF (typically 10% chopped CF). Reference values from Spectrum PCTG CF10: tensile yield 70 MPa (+59% vs unfilled), elongation @ break 5% (–98%), notched Izod 4 kJ/m^2 (–96%), HDT @ 0.455 MPa 78 °C (+3%). The CF gives strength and stiffness but trades away the headline impact toughness; PCTG-CF behaves more like PETG-CF or short-fiber nylon than unfilled PCTG. Use for stiff, dimensionally stable fixtures and brackets, not impact-loaded parts. Hardened nozzle mandatory.

PCTG-GF (typically 10% GF). Similar trade as CF, slightly less stiff, lighter color (white/translucent matte). 3D-Fuel, Spectrum, and Fiberlogy offer 10% GF grades. Processing window matches CF closely. Aggressive drying because fiber surface area increases moisture uptake.

Tritan-based grades. Where a vendor specifies Tritan resin (or the property envelope strongly implies it: notched Izod >15 kJ/m^2, HDT >80 °C, <1% haze), expect better dishwasher/hot-fluid behavior, marginally better UV, and a small ($3-7/kg) price premium. For repeatable food-contact or medical-adjacent work, Tritan-based PCTG is the defensible choice.

Recycled / ReFuel. 3D-Fuel's ReFuel Pro PCTG is built from regrind. Mechanical envelope is essentially indistinguishable from virgin Pro PCTG on tensile and impact; color is restricted (natural, black) and diameter tolerance is the same ±0.02 mm. Useful for jigs and prototyping where the recycled story matters and color flexibility doesn't.

8.7 Print process and calibration

Parameter	Range	Notes
Nozzle (°C)	240–270	Vendors split: Spectrum 250–270; 3D-Fuel 260–280; Fiberlogy 230–260
Bed (°C)	70–90	PEI smooth/textured; glue stick on glass; PVP coating
Chamber	open or passively warm	No active heating required
Part cooling fan (%)	30–60	Lower than PLA, higher than ABS; 100% acceptable on small features
Print speed (mm/s)	40–80 body / 30–50 wall	High melt strength tolerates fast moves; stringing increases
Max volumetric flow (mm^3/s)	8–12	20+ on high-flow hotends (CHT, Bambu HF); always calibrate
Retraction (direct drive)	0.6–1.2 mm @ 30–45 mm/s	
Retraction (Bowden)	3–6 mm @ 30–45 mm/s	
Pressure advance	0.03–0.06	3D-Fuel Pro PCTG calibrated at 0.053 in author's testing (see Appendix B)
XY shrinkage compensation	0.2–0.5%	Some users report 2–2.5% scaling needed for fit to non-PCTG mates
Drying	65–70 °C, 4–6 h	Required for transparent prints; resin TDS spec is 88 °C

Table 8.6 — PCTG starting print parameters (0.4 mm nozzle). Per-spool calibration mandatory; the Spectrum-vs-3D-Fuel temperature split reflects real composition differences.

8.8 Slicer-level cautions specific to PCTG

- **Avoid grid infill.** Grid lines cross within the same layer, dragging the nozzle through extruded material twice and depositing PCTG on the nozzle until it eventually drops onto the part. 3D-Fuel's published process profiles override the typical slicer default to cubic or gyroid for exactly this reason.
- **Disable avoid_crossing_perimeters.** A travel-path bug in current major slicer branches (2.9.x era) causes phantom artifacts when this option is enabled with PCTG/PETG-class materials; the workaround is to leave the option off.
- **Watch top-surface dishing.** On low-density sparse infill (≤15%) thin top surfaces can pull down between rafters as PCTG cools — same mechanism as the PC Blend issue, just less severe. Use 6–8 top layers, 20–25% cubic infill, or both.
- **Multi-material with PETG and PLA.** PCTG bonds well to PETG; pair freely in multi-material prints. PCTG bonds poorly to PLA — useful as a release interface for PLA supports, deliberately. Purge volumes between PCTG and PETG can be lower than the typical slicer default.

8.9 Application fit

Choose PCTG when: impact loading or drop survival matters (tool housings, drone bodies, RC parts, lab equipment); ductile failure mode is required (living hinges, snap-fits with more than a few cycles, clips, latches); optical clarity matters (light pipes, transparent enclosures, fluid sight glasses, optical mockups — 90% transmittance at <1% haze is materially better than PETG clear); food and drinking-water contact at the resin level (Tritan carries FDA 21 CFR food-contact compliance and NSF/ANSI 51/61 at the resin level, verify per-filament additives); cold-weather toughness (PCTG retains useful notched Izod at –40 °C where PETG embrittles).

Do not choose PCTG when: heat above ~80 °C is in scope (use PC, PC-CF, ASA, or PPA); long-term outdoor UV (use ASA); wear surfaces under sliding load (use POM, PEEK, or iglidur); solvent smoothing is part of the workflow (no common workshop solvent works on PCTG); lowest-cost prototyping (PETG saves $10–20/kg with comparable printability).

8.10 Post-processing

Method	PCTG suitability	Notes
Sanding (dry/wet)	Good	Wet sand 320 → 800 → 1500 for matte; keep moving, keep wet
Mechanical polishing	Good	After 2000 grit, plastic polish or buffing for near-transparent on clear grades
Acetone vapor smoothing	Not effective	Attacks but doesn't flow; produces degraded matte surface
Ethyl acetate vapor smoothing	Marginal	Better than acetone; PCTG response is inconsistent
MEK or DCM smoothing	Possible / hazardous	DCM dissolves; both require fume hood
Heat-gun smoothing	Possible	Brief distant passes melt a thin surface skin; easy to overshoot
2K epoxy coating (XTC-3D)	Excellent	Reliable smooth surface; adds layer thickness
Painting	Good	Sand to 320; plastic-bonding primer (SEM, Bulldog); then topcoat
Annealing	Limited gain	Amorphous; no crystallization; small stress-relief gain
Threading / tapping	Excellent	Ductility holds threads better than PETG
Gluing	Good	CA for fast; Loctite Plastic Bonder for structural

Table 8.7 — Post-processing options for PCTG. The chemical resistance that makes PCTG service-friendly also limits the solvent-smoothing workflow.

8.11 Open questions and honest uncertainty

Resin identity is rarely disclosed. Most filament TDSs identify the material as “PCTG” without naming the resin. Whether any given spool is Tritan, generic Eastman PCTG (Eastar series), SK Skygreen or a Chinese copolyester materially affects performance — and is generally only inferable from price and property envelope.

Z-direction values are largely unpublished. Vendors publish XY tensile and Izod; Z values can be 40–60% lower. Engineering design requires bracket testing on the actual machine.

UV field-life data is sparse. “UV resistant” on a TDS rarely comes with hours of QUV exposure or color-shift data. Outdoor service life claims should be tested, not trusted.

Food-contact compliance does not transfer to printed parts. Resin certifications (FDA 21 CFR, NSF 51, NSF 61) apply to the resin as molded. FDM layer lines harbor bacteria and contamination from hotend residues; for repeated-use food contact, coat or seal. Filament-level certifications typically cover the resin plus additives — not the printed surface.

Independent third-party test coverage of PCTG remains thin relative to PLA and PETG. Cross-brand impact and tensile comparisons under uniform print conditions remain the largest open empirical gap for this material.

9. PET and reinforced PET grades

Polyethylene terephthalate is the parent polyester of the family this Part covers: PETG and PCTG are both glycol-modified descendants of PET, engineered specifically to defeat the property that makes unmodified PET awkward to print. That makes PET worth a chapter of its own — not because plain PET filament is common (it is not), but because understanding why it is uncommon explains the entire copolyester category, and because the two reinforced grades that *are* printable in practice, PET-CF and PET-GF, behave unlike anything else in Part III.

9.1 Chemistry: the parent polyester

PET is the condensation polymer of terephthalic acid (TPA) and ethylene glycol (EG) — a rigid aromatic diacid joined to a short, regular two-carbon diol. The regularity is the point: an unbranched, symmetric backbone packs readily into crystalline domains. PET is therefore a strongly semi-crystalline polymer, with a melting transition near 250–260 °C and a glass transition near 70–80 °C. In its crystalline form it is the material of drink bottles, polyester fiber, and thermoformed packaging — strong, stiff, chemically durable, and inexpensive at industrial scale.

That same crystallinity is what makes PET difficult as an FDM feedstock. A polymer that crystallizes readily also crystallizes *unevenly* during the rapid, directional cooling of fused-filament deposition: crystalline and amorphous regions form at different rates in different parts of the bead, they have different densities, and the resulting differential shrinkage drives warping, poor layer registration, and opacity. PETG and PCTG exist to solve exactly this. Substituting some of the ethylene glycol with the bulky, ring-shaped cyclohexanedimethanol (CHDM) disrupts the backbone regularity enough that the polymer can no longer crystallize on FDM timescales — it stays amorphous, prints predictably, and finishes clear. PETG is the glycol-modified grade; PCTG is the higher-CHDM grade with greater toughness. Both trade PET's crystalline stiffness and temperature resistance for printability.

One point of vocabulary is worth settling here, because it causes recurring confusion. PLA is also a polyester — Part II covers it as its own family — so a reader is entitled to ask why it is not simply folded into this Part. The answer is that “polyester” names a bond, not a behavior: any polymer whose backbone is built from ester linkages qualifies. PET, PETG, and PCTG are *aromatic* copolyesters — their stiffness and thermal resistance come from the benzene ring in the terephthalic-acid unit. PLA is an *aliphatic* polyester, built from lactic-acid units with no aromatic ring at all. That single structural difference cascades into everything a practitioner cares about: PLA is bio-derived, prints cold, barely warps, and softens well below 60 °C, whereas the aromatic PET family prints hot, is hygroscopic, and holds its shape far higher. Grouping by printing behavior — PLA in Part II, the aromatic copolyesters in Part III — is therefore more useful to the reader than grouping by the shared ester bond, even though the latter is the stricter chemical taxonomy.

9.2 Why plain PET is uncommon as a filament

Unmodified PET is sold as filament only rarely, and it is worth being explicit about why rather than treating it as a routine option. Three factors compound. First, the crystallization behavior above: a part can warp, delaminate, or finish cloudy depending on cooling history, and the cooling history is hard to control across a whole print. Second, PET is aggressively hygroscopic and must be printed dry — wet PET hydrolyses at melt temperature, and chain scission permanently lowers the molecular weight, so a poorly dried spool yields brittle parts no print setting can recover. Third, PETG already occupies the niche plain PET would fill: it is easier to print, nearly as strong, clearer, and costs no more. For an unreinforced polyester, there is little practical reason to choose PET over PETG, and the market reflects that. Where PET earns its place is reinforced — and there the calculus changes completely.

9.3 Reinforced grades: PET-CF and PET-GF

Adding chopped carbon fiber (PET-CF) or short glass fiber (PET-GF) to a PET matrix does something more useful than simply stiffening it. The fibers act as nucleation sites and as a physical brake on shrinkage: they give crystallization a controlled, distributed set of starting points and they mechanically restrain the matrix as it cools, so the differential-shrinkage warping that plagues unfilled PET is substantially suppressed. The reinforcement that is added for stiffness also happens to fix PET's core printability problem. The result is a pair of filaments that are stiffer and more dimensionally stable than PETG, with a usefully higher service temperature, and that print with far less drama than unfilled PET ever would.

PET-CF is the stiffer of the two and the lighter relative to PET-GF. Chopped carbon fiber raises modulus sharply; it also raises the compound's density slightly over the base resin, since carbon fiber is denser than PET — but the increase is far smaller than the glass-fiber equivalent, which is why PET-CF parts come out lighter than PET-GF parts of the same geometry. Parts are dark grey to black with a matte finish, dimensionally stable, and well suited to jigs, fixtures, and structural brackets where rigidity matters more than impact toughness. As with every carbon-filled filament, the trade is abrasion: a hardened or wear-resistant nozzle is mandatory, and the headline impact toughness drops well below that of unfilled PETG — PET-CF behaves like a stiff, brittle composite, not a ductile polymer. **PET-GF** trades some of that stiffness for a tougher, less brittle failure mode and a lower price; glass-filled parts are typically white or translucent-matte. Both grades are hygroscopic and fiber-reinforced filaments take up moisture faster than their base resin because the fiber–matrix interface offers additional surface area — drying is not optional.

Property	PETG (reference)	PET-CF	PET-GF
Reinforcement	none (amorphous)	chopped carbon fiber	short glass fiber
Stiffness	baseline	much higher	higher
Impact toughness	high (ductile)	low (brittle composite)	moderate
Dimensional stability	good	excellent	excellent
Service temperature	baseline	higher than PETG	higher than PETG
Nozzle	brass acceptable	hardened mandatory	hardened mandatory
Typical appearance	clear / tinted	matte black / grey	white / matte

Table 9.1 — Reinforced PET grades against PETG as the familiar reference point. The columns are qualitative by design: published datasheet values for PET-CF and PET-GF vary widely between vendors because fiber loading, fiber length, and base-resin grade are all uncontrolled variables, and a filament-level number is not portable between brands. Treat the table as a direction-of-effect guide and calibrate against the specific spool in hand.

9.4 Print process

The reinforced PET grades print hotter than PETG and demand the same discipline as any fiber-filled engineering filament: dry the spool, fit a hardened nozzle, and calibrate rather than trust the datasheet. The worked figures below are from a calibrated Fiberon PET-GF15 profile on a Core One with a 0.4 mm hardened (E3D Diamondback) nozzle, and are offered as a concrete, reproducible starting point rather than a universal specification — a different PET-GF spool, or a PET-CF grade, will need its own calibration pass.

Parameter	Fiberon PET-GF15 (calibrated)	Notes
Nozzle temperature	290 °C	hotter than PETG; the glass loading raises melt viscosity
Nozzle	0.4 mm hardened (E3D Diamondback)	mandatory for any fiber-filled grade
Part cooling	fans off	cooling promotes uneven crystallization and weakens layer bonds
Extrusion multiplier	~0.96	calibrated by single-wall measurement, not assumed
Pressure advance	~0.040 (starting value)	stored in the filament profile; tune per machine
Drying	mandatory before printing	fiber interface accelerates moisture uptake

Table 9.2 — A calibrated PET-GF15 process profile (Core One, 0.4 mm hardened nozzle). The extrusion-multiplier and pressure-advance values are the result of the standard calibration workflow — temperature tower, volumetric-flow ceiling, extrusion multiplier by single-wall measurement, then pressure advance — not datasheet figures. Fans-off is deliberate: like the semi-crystalline engineering filaments, reinforced PET bonds layers better and warps less without part cooling.

Two process points carry over from the rest of Part III. Bed adhesion is straightforward — the polyester chemistry grips PEI well, as it does for PETG and PCTG — but the higher nozzle temperature and the absence of part cooling make a clean first layer and a stable chamber more important than they are for plain PETG. And the abrasion caution is not negotiable: a brass nozzle will measurably wear within a single large PET-CF or PET-GF print, after which extrusion consistency degrades.

9.5 Application fit

Choose PET-CF when: the part is a jig, fixture, or structural bracket where stiffness and dimensional stability are the priority and impact loading is not; weight matters; and a hardened nozzle is available. **Choose PET-GF when:** the same stiffness-and-stability requirement applies but the part may see impact or handling stress, where PET-GF's less brittle failure mode is worth the modest loss of rigidity, and where cost is a consideration. **Choose plain PETG or PCTG instead when:** the part needs ductility, optical clarity, or food-contact compliance, or when a hardened nozzle is not available — the reinforced PET grades give up all of those. **Reach past PET entirely when:** the service temperature or chemical demands exceed what a reinforced polyester delivers, at which point the polyamide and polycarbonate families in the Parts that follow are the right place to look.

Part IV

Styrenics Family

The styrenics: ABS, ASA, and HIPS - the original engineering-adjacent commodity filaments, defined by styrene content, enclosure needs, and solvent-smoothing behavior.

10. Styrenics: ABS, ASA, HIPS

The styrenic family is built on polystyrene chemistry with various copolymer additions for toughness, weatherability, or solubility. Its three FDM-relevant members — ABS, ASA, and HIPS — share an acetone-based vapor-smoothing capability and a characteristic warping behavior that defines how they are printed. The family has been partially displaced from desktop FDM by PCTG and the polycarbonate blends for general engineering use, but it remains the most cost-effective enclosed-print material, the canonical choice for outdoor service in the case of ASA, and the only widely practical soluble-bath support for the family in the case of HIPS. This chapter treats the shared chemistry first, then each material in turn, then the process, post-processing, and selection questions common to all three.

10.1 Styrenic chemistry: the shared backbone

All three materials are amorphous polymers built on a polystyrene backbone. Polystyrene itself is rigid, glossy, easy to process, and brittle; the styrenic engineering filaments are all strategies for keeping the processability and gloss while defeating the brittleness. Because the backbone is amorphous, none of the three has a true melting point — they soften progressively above a glass transition near 100 °C rather than melting sharply — and all three are soluble in the same class of solvents, which is why a single post-processing technique (solvent vapor smoothing) applies across the family.

ABS (acrylonitrile-butadiene-styrene) is a terpolymer: acrylonitrile contributes rigidity and chemical resistance, butadiene contributes impact toughness as a discrete dispersed rubber phase, and styrene contributes processability and surface gloss. **ASA** (acrylic-styrene-acrylonitrile) replaces ABS's butadiene with an acrylate elastomer. That single substitution is the whole point of ASA: butadiene's carbon–carbon double bonds are the site of UV photo-oxidation, so an ABS part chalks, yellows, and embrittles within months of outdoor exposure, whereas the saturated acrylate rubber in ASA has no such double bonds and survives years of UV. **HIPS** (high-impact polystyrene) is the simplest of the three: polystyrene impact-modified with a discrete polybutadiene phase, with no acrylonitrile. It is less rigid and less chemically resistant than ABS, but its polystyrene base makes it soluble in limonene — the property that gives HIPS its main role as a soluble support material.

The shared amorphous backbone also explains the family's defining print difficulty. An amorphous polymer with a glass transition near 100 °C contracts substantially as it cools from melt to room temperature, and because the contraction is continuous rather than released at a sharp crystallization point, a styrenic part builds internal stress layer by layer as it prints. That stress expresses itself as warping and as interlayer cracking — the larger the part and the cooler its surroundings, the worse both become. The entire styrenic print process is organized around managing that stress.

10.2 ABS

ABS is the original engineering filament and remains the reference against which the family is judged. Its glass transition near 105 °C, tensile strength of roughly 30–45 MPa, modulus near 2 GPa, and elongation of 10–40 % describe a stiff, moderately tough material with usable heat resistance well above PLA or PETG. Its headline notched-Izod impact of roughly 15–25 kJ/m^2 reflects the butadiene rubber phase doing its job.

The cost of that property set is printability. ABS shrinks 1–2 % on cooling, and on parts larger than about 100 mm in any dimension the resulting warp is severe without an enclosure. The practical consequence is that ABS is an enclosed-printer material: a passive enclosure holding the chamber at 40–50 °C is the realistic minimum, and prints will still lift at the corners without good first-layer adhesion and a brim. ABS also emits styrene and fine particulate during printing; ventilation or filtration is a meaningful consideration rather than an optional one, and is treated in the emissions material of Chapter 5. Where ABS earns its place is the combination of low cost, acetone vapor smoothing, and moderate heat resistance — no other filament family delivers all three at ABS's price.

10.3 ASA

ASA has a glass transition near 100 °C and tensile and stiffness figures close to ABS; mechanically the two are near-equivalent. The difference that matters is environmental. ASA's saturated acrylate rubber phase gives it a large UV-stability advantage — outdoor service life measured in years rather than the months an ABS part lasts before it chalks and embrittles — which makes ASA the canonical engineering filament for parts that live outdoors. ASA prints slightly hotter than ABS, typically 250–270 °C at the nozzle with a 105–110 °C bed and an enclosed chamber, and it responds to acetone smoothing in the same way ABS does.

The figures below are the author's own calibration values for Prusament ASA on a Core One with a 0.4 mm PCD (E3D Diamondback) nozzle. The calibration was in progress at the time of compilation: the nozzle-temperature, volumetric-flow, and extrusion-multiplier values are settled, Z-shrinkage compensation was intentionally skipped, and pressure-advance and XY-shrinkage calibration were still pending. They are offered as a concrete, reproducible starting point for one specific filament-and-machine combination, not a universal ASA specification — Appendix B carries the full worked example.

Parameter	Prusament ASA (calibrated)	Notes
Nozzle temperature	260 °C	settled; within the 250–270 °C ASA range
Max volumetric flow	9.5 mm^3/s	ceiling from the volumetric-flow calibration step
Extrusion multiplier	1.03	calibrated by single-wall measurement
Z-shrinkage compensation	intentionally skipped	not pursued for this profile
Pressure advance	calibration pending	to be tuned and stored in the filament profile
XY-shrinkage compensation	calibration pending	to be measured on the standard test artifact

Table 10.1 — In-progress calibration profile for Prusament ASA (Core One, 0.4 mm PCD nozzle). The settled values follow the standard calibration workflow; the pending rows are noted honestly rather than filled with datasheet figures. Treat this as a worked example of the calibration method applied to one ASA spool, not a portable specification.

10.4 HIPS

HIPS has a glass transition near 90–100 °C, tensile strength around 34 MPa, and modulus near 1.9 GPa — softer and less rigid than ABS, and without ABS's acrylonitrile-derived chemical resistance. As a build material it is used for lighter-weight cosmetic parts, but this is a minor role and HIPS as a standalone model material is uncommon. Its more important use is as a soluble support: HIPS dissolves in limonene while ABS and ASA do not, so a HIPS support structure can be removed from an ABS or ASA print by a limonene bath that leaves the model untouched. HIPS prints at roughly 230–250 °C nozzle and 100–110 °C bed, with the same enclosure and warp considerations as the rest of the family.

Two cautions apply specifically to HIPS. Limonene is a skin-sensitizer and the bath process needs appropriate handling and ventilation. And HIPS is more aggressively attacked by acetone than ABS is — limonene smoothing works as a finishing technique for HIPS, but acetone, which smooths ABS cleanly, will over-etch a HIPS surface.

10.5 Property envelope

The three materials are close enough mechanically that a side-by-side comparison is the clearest way to see where they differ. The figures are representative filament-form ranges; as with every polymer in this volume, brand-to-brand variation is real and a specific spool should be calibrated rather than assumed from the table.

Property	ABS	ASA	HIPS
Glass transition (T_g)	~105 °C	~100 °C	~90–100 °C
Tensile strength	30–45 MPa	similar to ABS	~34 MPa
Modulus	~2 GPa	similar to ABS	~1.9 GPa
Elongation at break	10–40 %	similar to ABS	lower than ABS
Notched Izod impact	15–25 kJ/m^2	similar to ABS	moderate
UV stability	poor (months outdoors)	excellent (years outdoors)	poor
Chemical resistance	moderate	moderate	lower (no acrylonitrile)
Solvent smoothing	acetone	acetone	limonene
Primary role	cost-driven engineering parts	outdoor service parts	soluble support

Table 10.2 — Styrenic property envelope. ABS and ASA are mechanically near-equivalent; the columns that actually separate the family are UV stability and the choice of smoothing solvent. HIPS trades rigidity and chemical resistance for limonene solubility, which is what makes it useful as a support.

10.6 Print process and calibration

The styrenic print process is, in essence, stress management. The consolidated parameters below are starting points; the reasoning behind them is consistent across the family. Bed temperature is kept high to hold the first layers above the point where they would begin to contract and lift. The chamber is enclosed so that the whole part cools slowly and evenly, which limits the layer-to-layer stress that drives both warping and interlayer cracking. Part cooling is used sparingly or not at all — aggressive fan cooling freezes each layer before it has bonded fully to the one below, weakening the part and worsening warp. A brim or raft is routine on anything large. PEI grips all three materials strongly, so adhesion is rarely the failure mode; warp-driven corner lift is.

Parameter	ABS	ASA	HIPS
Nozzle temperature	240–260 °C	250–270 °C	230–250 °C
Bed temperature	95–110 °C	105–110 °C	100–110 °C
Chamber	enclosed, passive 40–50 °C	enclosed	enclosed
Part cooling	minimal to none	minimal to none	minimal to none

Parameter	ABS	ASA	HIPS
Bed surface	PEI; brim for large parts	PEI; brim for large parts	PEI
Shrinkage	1–2 %	similar to ABS	similar to ABS

Table 10.3 — Consolidated styrenic print parameters. The ranges overlap heavily because the three materials share a backbone and a failure mode; an enclosure and restrained part cooling matter more than the exact temperature within these bands. Calibrate the specific spool — the worked ASA example in Table 10.1 shows the method.

10.7 Post-processing: solvent vapor smoothing

Solvent vapor smoothing is the styrenic family's signature post-process and a genuine advantage over most other filament families. Suspending a part in the solvent vapor briefly liquefies the outermost surface layer; surface tension then pulls that layer flat, erasing layer lines and producing a glossy, near-injection-moulded finish. The process also closes surface porosity, which improves the part's resistance to water ingress.

ABS and ASA are smoothed with acetone, applied as a controlled vapor rather than by immersion. The technique is forgiving on these two materials: a short exposure produces a light satin finish, a longer one a high gloss, and the surface recovers its hardness once the residual solvent has fully evaporated, which takes time and should not be rushed. HIPS is smoothed with limonene instead — acetone attacks HIPS more aggressively than it attacks ABS and tends to over-etch the surface. The trade-offs to weigh are that vapor smoothing slightly softens fine detail and edges, that it modestly changes dimensions as the surface reflows, and that both solvents demand ventilation and appropriate handling — acetone for its flammability, limonene for its skin-sensitization potential.

10.8 Multi-material: HIPS as breakaway support

On dual-hotend or IDEX hardware, HIPS pairs well with the polycarbonate blends as a breakaway support interface. The PC-to-HIPS adhesion is intermediate by nature — strong enough to hold the support in place during the print, weak enough to release cleanly on cool-down without any dissolution step. A practical workflow for PC Blend with HIPS breakaway support is a PEI or garolite plate prepared with Magigoo PC, with two layers of PCTG interface (rectilinear, 0.2 mm spacing, zero Z-gap) laid above the HIPS support body. The PCTG interface releases more cleanly than HIPS printed directly against PC Blend, and it avoids the limonene bath entirely — a meaningful simplification when the support only needs to break away rather than dissolve.

10.9 Brand landscape

ABS is a commodity filament available from essentially every manufacturer, and the practical split is between basic ABS and the impact-modified or low-warp engineering grades that several vendors market under their own names — the latter are easier to print and worth the premium for larger parts. ASA has a smaller but well-established field: FormFutura ApolloX, Prusament ASA, Fiberlogy ASA, Polymaker PolyLite ASA, and Overture ASA are representative of the brand-leading products, and ASA is the grade where buying a known filament rather than the cheapest available spool most clearly pays off, because outdoor performance depends on the UV-stabilizer package. HIPS is widely available and inexpensive; since its dominant use is as a support material, spool-to-spool consistency and clean limonene solubility matter more than mechanical figures when selecting it.

10.10 Application fit and current market position

Choose ABS when: the part is a cost-driven engineering component that needs moderate heat resistance or acetone vapor smoothing — under-hood automotive prototyping, electronics enclosures, and similar — and an enclosed printer is available. **Choose ASA when:** the part will see outdoor service — sprinkler housings, marker stakes, outdoor electronics enclosures, garden equipment — where PCTG would weather and a polycarbonate blend would be overkill; ASA is the right answer for UV exposure. **Choose HIPS when:** a soluble or breakaway support is needed for an ABS or ASA print, or, less often, for a light cosmetic part. **Choose something else when:** the part needs ductility, clarity, or food-contact compliance, or when no enclosure is available — PCTG is the easier engineering filament, and the polycarbonate blends cover the higher-temperature and higher-toughness cases. The styrenic family has been partially displaced from desktop FDM for general engineering use, but ABS on cost, ASA on outdoor durability, and HIPS as a support each retain a niche that the displacing materials do not fully cover.

Part V

Polyolefins

Polypropylene — the second-most-produced commodity plastic in the world and the hardest commodity polymer to print on consumer FDM hardware — and the smaller polyethylene niche. The defining challenges are low-surface-energy bed adhesion and high crystallization shrinkage; the fixes are dedicated PP-coated build sheets and fiber reinforcement.

11. Polypropylene (PP) — deep dive

Polypropylene is a polyolefin commodity polymer with global production around 90 million tonnes annually — second only to polyethylene. The bulk is consumed in injection molding and extrusion: packaging, automotive interior trim, textiles, consumer products. The property set that drives its industrial dominance — low density (0.90–0.91 g/cm^3, lower than every other major thermoplastic), high chemical resistance, high fatigue resistance, low water absorption, food-contact compliance, and easy recyclability — also makes it attractive for 3D printing. The same property set, however, makes PP actively hostile to layer-by-layer extrusion.

Three constraints dominate PP process design regardless of brand. First, neither PEI nor glass nor powder-coated build plates adhere to PP without an intermediate layer; this layer is either a dedicated PP-on-PP plate, polypropylene packing tape, or a PP-specific adhesive. Second, fiber-filled grades require a hardened or wear-resistant nozzle without exception. Third, part cooling must be minimized for layer adhesion; PP does not tolerate the aggressive cooling profiles routine for PLA and PETG. The materials science literature has spent the better part of a decade chipping away at these issues, primarily by adding glass or carbon fiber and by developing PP-specific bed adhesion chemistry.

11.1 Homopolymer vs copolymer

Commercial PP falls into two broad categories. **Homopolymer PP** is pure propylene chains; stiffer, higher tensile strength, more crystalline, brittle at low temperatures, warps aggressively. **Copolymer PP** — either random copolymer with a few percent ethylene distributed along the chain, or impact copolymer (block or heterophasic) with a discrete ethylene-propylene rubber phase — trades some stiffness and crystallinity for greatly improved impact performance (especially below 0 °C) and somewhat better printability.

Most successful 3D printing PP grades are copolymers: 3DXTech CarbonX PP+CF, Braskem FL900PP, and the engineering-grade Fiberlogy and Recreus products are all explicitly built on PP copolymer matrices. Pure homopolymer PP is rare in the consumer FFF market because the elevated warp tendency makes large parts effectively unprintable on most hardware.

11.2 Filament variants

Variant	Typical loading	Position
Unfilled PP	0%	Highest elongation (>100%); living hinges, watertight containers; hardest to print
PP-GF	15–30% glass fiber	Most common engineering grade; warp largely tamed; cost-effective
PP-CF	15–30% chopped CF (often recycled)	Highest stiffness and lowest dimensional change; matte black; abrasive
PP-Talc / mineral	20–40% talc/$CaCO_3$	Common in injection-molded grades, rare in filament; doesn't address warp
Recycled PP / R PP	100% PCR/PIR	Fiberlogy R PP; ocean-recovered PP-GF (Porthcurno); property envelope matches virgin

Table 11.1 — PP filament variants. Fiber reinforcement is the principal lever for printability; CF and GF each have application-driven trade-offs.

11.3 Property envelope

Property	Unfilled PP	PP-GF (15–30%)	PP-CF (15–30%)
Density (g/cm^3)	0.90–0.91	1.05–1.15	0.91–1.00
Tensile strength, XY (MPa)	15–25	30–50	25–45
Tensile modulus, XY (GPa)	1.0–1.4	2.0–3.0	2.0–4.0
Elongation @ break (%)	100–600	3–10	3–6
Flexural modulus (GPa)	0.8–1.2	2.0–3.0	1.8–3.5
Charpy notched (kJ/m^2)	5–15	7–12	10–15
HDT @ 0.45 MPa (°C)	85–100	115–140	115–160
HDT @ 1.80 MPa (°C)	55–75	90–115	95–120
Shore D	65–72	67–72	60–65
Moisture absorption (%)	<0.05	0.05–0.15	<0.05
Interlayer adhesion (MPa)	10–15	15–20	10–15
Volumetric shrinkage tendency	high (warps)	low	very low
Living-hinge capable	yes	no	no
Hardened nozzle required	no	yes	yes

Table 11.2 — PP property envelope by variant. HDT figures should be read cautiously: the 158 °C value quoted for some PP-CF grades at 0.45 MPa is consistent with the test method but does not mean the part is functional under load at that temperature. PP creeps above 60–70 °C regardless of HDT figure.

Chemical resistance is where PP genuinely excels. Across vendor data and the published literature, PP demonstrates resistance to dilute and concentrated acids (acetic, boric, hydrochloric, phosphoric, sulfuric), hydroxide bases (ammonium, sodium, potassium, barium, magnesium, calcium), most alcohols, aliphatic and aromatic solvents (acetone, ethanol, methyl ethyl ketone), salt solutions, and water up to 80 °C. PP is degraded by strong oxidizers (concentrated nitric acid, chromic acid, hot sulfuric acid above 60%) and exhibits creep when in sustained contact with non-polar hydrocarbon solvents at elevated temperature.

11.4 The printability problem

Why PP warps. PP is semi-crystalline with a melting transition near 160 °C and crystallization onset between 110 and 130 °C on cooling. Volumetric contraction from melt to room temperature is on the order of 1.5–2.5%, compared with about 0.4% for amorphous polymers like PETG. Layer-by-layer accumulation in an FFF print concentrates this in-plane shrinkage at part edges. The problem compounds with part dimension: a 20 mm cube prints fine; the same geometry scaled to 200 mm exhibits enough cumulative shrinkage force at the corners to overcome any standard bed adhesion. Glass and carbon fiber reduce in-plane shrinkage by one-half to two-thirds, which is the structural reason fiber-filled PP prints without an enclosure while unfilled PP often cannot.

Why PP doesn't stick to PEI. Bed adhesion is interfacial wetting plus intermolecular attraction. PEI has surface energy ~40 mN/m and depends on polar interactions to grip amorphous polymers; PP is a non-polar polyolefin with surface energy ~30 mN/m and cannot present polar groups for those interactions. The contact is nearly frictionless. Practical adhesion solutions all use PP-on-PP self-adhesion: a polypropylene surface on the bed, bed temperature soft enough to fuse the surface PP into the print's first layer, then cooling for release.

How reinforcement fixes both problems. Fibers don't crystallize, so they reduce volumetric shrinkage proportional to loading. Fibers align with extrusion direction during printing and physically constrain matrix shrinkage anisotropically — less in the print direction, more perpendicular. A 30% glass-loaded PP exhibits perhaps one-third the linear shrinkage of unfilled PP in the print direction. Sufficient for enclosure-free printing of moderate-size parts. Does not change surface energy: bed adhesion strategy is identical to unfilled PP.

11.5 Brand landscape

Prusament PP Carbon Fiber

Manufactured by Prusa Polymers, Czech Republic; carbon fiber recycled from manufacturing waste and end-of-life CF composites. Density 0.91 g/cm^3, 0.03% 24-hour moisture absorption, HDT 158 °C / 115 °C (at 0.45 and 1.80 MPa). Tensile yield 27.3 ± 0.7 MPa horizontal, 30.7 ± 0.3 MPa vertical; modulus 2.1 / 2.5 GPa; Charpy unnotched 19 kJ/m^2 . 650 g spools. Print at 270 ± 10 °C nozzle, 85 ± 10 °C bed, ≤40 mm/s, fan off, extrusion multiplier 1.09. Prusa PP sheet recommended; PEI smooth + PP packing tape is the documented alternative. No enclosure required.

Prusament PP Glass Fiber

Glass-fiber sibling of PP-CF. Density 1.12 g/cm^3, MFR 14.7 g/10 min, HDT 138.3 / 112.6 °C, tensile yield 40.3 / 48.8 MPa horizontal/vertical, modulus 2.1 / 2.5 GPa, Charpy unnotched 17.6 / 26.9 kJ/m^2 . 850 g spools, natural color only. Print at 245 ± 10 °C, 95 ± 10 °C bed, ≤50 mm/s, extrusion multiplier 1.03, infill/perimeter overlap 15% (notably lower than the 40% used for PP-CF). PP sheet, hardened nozzle. PP-GF is the stiffer, higher-HDT, lower-cost choice within the Prusament PP family.

Braskem FL900PP family

Braskem is the largest polyolefins producer in the Americas and the primary supplier of base PP resin to multiple filament compounders. The FL900PP-CF flagship is 100% recycled carbon fiber. Tensile strength approximately 6× unfilled PP. 700 g spools. Product line also includes FL100PP (unfilled prototyping), FL105PP (high fatigue), FL500PP-GF (glass fiber); pellet products GR100PP and GR105PP for FGF. Braskem's published case study on a drone arm documents 37% mass reduction vs the factory part with 63% stress reduction at impact and ~4% improved flight time — one of the few publicly available performance benchmarks for any PP-CF product.

3DXTech CarbonX PP+CF

Manufactured in Grand Rapids, Michigan. Specialty PP copolymer matrix reinforced with high-modulus chopped CF. 3DXTech holds a patent-pending formulation claim around improved thermal properties and low shrinkage vs competitor PP-CF. 750 g spools (volume of a 1 kg ABS/ASA spool due to density). Recommended layer height 60% of nozzle diameter, hard floor 0.25 mm; below this, fiber-loaded melt back-pressure causes jams and filament-drive grinding.

Fillamentum PP 2320

Industrial-grade unfilled PP. Density 0.96 g/cm^3 (above typical unfilled PP, suggesting mineral content), MFR 7.4 g/10 min. Tensile strength 23 MPa, elongation 20%, modulus 1400 MPa, Charpy unnotched 184 kJ/m^2 (consistent with impact-modified copolymer). Print at 225–245 °C, 90–105 °C bed, 20–40 mm/s, brim required, Magigoo PP recommended. 600 g spools, natural/black/white. Documentation is explicit: *“printing with polypropylene is extremely demanding and requires precise preparation.”* Food-contact declarations on request. Service range –40 to 100 °C; marketed for orthopedic braces among other applications.

Fiberlogy PP and R PP

Virgin Fiberlogy PP and 100% recycled R PP using PCR/PIR feedstock. Density 1.05 g/cm^3 (filler content beyond base copolymer), tensile 14 MPa, modulus 700 MPa, elongation >100%. Diameter tolerance ±0.02 mm. Print 220–250 °C nozzle, bed not strictly required when using packing tape (most users 80–100 °C). 0.75 kg and 2.5 kg spools.

FormFutura Centaur PP

Natural variant is food-contact compliant, dishwasher safe, microwaveable. Density 0.9 g/cm^3, elongation >600% (one of the highest published for any PP filament). Watertight single-wall printing explicitly supported. 500 g spools, 1.75 and 2.85 mm. Recommended 200–240 °C nozzle. The unusual elongation makes Centaur a strong choice for living hinges and vase-mode containers where wall flexibility is a design feature.

PPprint P-filament 721

Germany; polypropylene specialist. P-filament 721 extrudes at only 200–220 °C — the lowest temperature window of any commercial PP filament. The intended workflow uses PPprint substrates: P-surface 141 (PP adhesion film), P-adhesive 220 (attachment), P-roller 621 (install). Prints release by heating the bed to 110 °C. Bed runs cold (20 °C steady-state, 50–70 °C first layer) during printing, deferring heat to part removal — this avoids the long-soak warp problem Braskem documents at higher bed temperatures. P-filament 721 is biocompatible per DIN EN ISO 10993-5; the printability-optimized formulation is not FDA food-contact compliant. PPprint also produces P-support 279, a dedicated PP-compatible breakaway support — important since most general-purpose supports don't adhere to PP at all.

UltiMaker PP, Recreus PP3D / PP-GF, generic / Sunlu / Yousu

UltiMaker PP: 500 g spools, 2.85 mm only, natural color, designed primarily for the UltiMaker printer ecosystem. Print 220–240 °C / 80–100 °C, fan 50%. NFC verification and pre-built slicer profiles are the ecosystem value; price-per-kg unfavorable outside that ecosystem. **Recreus PP3D and PP-GF** (Spain): PP-GF developed with Repsol; standard PP-GF envelope. 0.4–0.6 mm nozzles, hardened steel minimum, 0.2 mm layer height optimal. Historical Recreus PP shipped with a dedicated PP adhesive for PEI bed use as low as 40 °C — the cold-bed approach later refined by PPprint. **Generic / Sunlu / Yousu / Eryone / Iemai**: Chinese unfilled PP at roughly half the named-brand price points. Sunlu PP community-reported calibration: nozzle 220 °C, bed 60 °C, EM 1.04, PP sheet mandatory, fan off, brim, avoid_crossing_perimeters disabled. Adequate for prototyping; not for documented mechanical performance or batch consistency.

11.6 Print parameters (consolidated)

Parameter	Unfilled PP	PP-GF	PP-CF
Nozzle (°C)	200–245	230–260	260–280
Bed (°C)	20–100*	85–105	75–95
Print speed (mm/s)	20–50	30–60	30–50
First-layer speed (mm/s)	10–20	15–25	15–25
Part cooling fan (%)	0–30	0	0 (bridges 100)
Layer height (mm)	0.15–0.30	0.20–0.32	0.25–0.32
Wall count	3–5	3–4	3–4
Extrusion multiplier	1.00–1.05	1.00–1.05	1.05–1.10
Retraction (DD, mm)	1–2	1–2	0.8–1.5
Retraction (Bowden, mm)	4–6	3–5	3–5
Brim	required	recommended	recommended
Enclosure	beneficial	optional	not required
Chamber temp (°C)	25–50	25–50	ambient
Nozzle hardness	brass OK	hardened	hardened
Drying	no	yes	yes

*Table 11.3 — PP starting print parameters. *Unfilled-PP bed temperature is dictated by the adhesion strategy: PP packing tape works at 80–100 °C; the cold-bed approach uses a 20 °C steady-state bed; the historical Recreus workflow used 40 °C on PEI with PP glue.*

Fan-off operation is essential for layer adhesion; PP's narrow window between crystallization onset and the temperature at which subsequent layers fuse means aggressive cooling produces visible layer separation. Walls 3–5 perimeters to compensate for modest interlayer strength (Prusament PP-CF TDS: interlayer adhesion 13 ± 1 MPa vs bulk filament tensile of 21 MPa). Top-surface dishing on sparse infill is a known failure mode — switch from gyroid to cubic at 20–25% density and increase top layers to 6–8.

11.7 Bed adhesion strategies (PP-specific)

Bed adhesion is the single most important variable in successful PP printing. Every successful approach presents a polypropylene-compatible surface for the print to grip — PEI, glass, and powder-coated steel will not hold PP by themselves.

PP-coated print sheets. Powder-coated PP build sheets are the cleanest and most reproducible approach. The Prusament-branded PP sheet (designed for the standard spring-steel magnetic bed format) and PPprint's P-surface 141 are the most widely-distributed options. Degrease with IPA, place on the magnetic bed, print. Bed 85–95 °C. Removal on cool-down; no residue. The sheet is a consumable that tolerates many prints before replacement. PPprint's system specifies cold-bed operation: PP film with self-adhesive backing or P-adhesive 220, installed with P-roller 621, bed at 20 °C steady-state and heated to 110 °C at end of print for release. Third-party PP stickers in standard build-plate sizes are widely available from online vendors.

PP packing tape. The original community solution and still the most cost-effective. Standard PP-based packing tape (Tesa, 3M, Scotch) applied to clean glass or PEI presents a PP surface; the acrylic adhesive holds it to the bed. Bed 80–100 °C, removal easy on cool-down. Drawbacks: application time on a 250 mm bed, and tape adhesive transfers to the bed (acetone removes it; acetone gradually attacks PEI if repeated). For users who switch between PP and other materials, packing tape on a dedicated glass bed is cleaner than tape on PEI.

Magigoo PP and Magigoo PP-GF. Liquid adhesive specifically formulated for PP, applied to clean glass, PEI, BuildTak, powder-coated, or Kapton. Spread evenly with the bottle's spring-loaded nib, cover the print area, brief dry. Bed 85–100 °C. Cleanup with water (water-soluble). Magigoo PP-GF is the stronger formulation for glass-filled PP and warp-prone unfilled-PP geometries with sharp corners or long flat sections. Community consensus across major FDM forums: the Magigoo PP family is the most reliable adhesive option for difficult PP prints, especially combined with a PP sheet for redundancy.

What does not work. Direct printing of PP on bare PEI, glass, mirror, BuildTak, FR-4/G10, or powder-coated steel does not adhere. Generic PVA glue stick is too thin and too polar. Hairspray and acrylic-based adhesives are similarly inadequate. IPA cleaning, essential for other materials, does not help PP adhesion — the controlling factor is surface chemistry, not contamination. PP-sheet manufacturers generally recommend soap and warm water over IPA for cleaning the PP sheet itself, because soap residue does not interfere with PP-on-PP adhesion.

11.8 Post-processing and chemical compatibility

PP cannot be vapor-smoothed: acetone, MEK, ethyl acetate, DCM, IPA, ethanol, methanol, and toluene all leave PP unaffected at room temperature. The chemical resistance that drives PP's applications forecloses most post-processing. Practical options are mechanical: wet sanding (220, 400, 600, 1000 grit) for matte finish; razor and rotary tools for support removal. Wet over dry to minimize airborne particles (respirable glass and CF fragments are documented hazards). PP does not deform under friction heat, making power-tool sanding viable without the smearing that occurs with PLA or PETG.

Painting and gluing are the principal limitations. Standard adhesives (CA, epoxy, polyurethane) bond poorly because they cannot wet the low-energy surface. Solutions: flame treatment (propane torch passes oxidize the surface and raise energy from 30 to 50–55 mN/m); corona treatment for production volumes; PP-specific primers (3M 4298UV, Loctite 770) followed by cyanoacrylate. 2K epoxy and XTC-3D coatings adhere modestly better than untreated direct adhesives but still benefit from surface activation. Mechanical interlocking (snap fits, dovetails, threaded inserts) is usually more reliable than chemical bonding for PP assemblies.

11.9 Multi-material and dual-hotend considerations

Multi-material printers that share a single nozzle (single-extruder MMU systems) or that operate two hotends in a single enclosure (dual-hotend, IDEX) face the same constraint: the chamber temperature and bed temperature must be compatible with every filament loaded in the print. Several printer manufacturers publish explicit compatibility categories at slice time; the underlying physics is the same regardless of which printer enforces it. **PP, PP-CF, and PP-GF are medium-temperature** materials in these schemes, alongside HIPS, PE, PE-CF, EVA, and PHA. High-temperature filaments (ABS, ASA, PC, PA, PA-CF, PA-GF, PA6-CF, PET-CF, PPS, PPS-CF, PPA-CF, PPA-GF, ABS-GF) cannot be mixed with PP in a single print because the chamber and bed temperatures required for the engineering material will degrade or warp the PP. Low-temperature filaments (PLA, PETG, PETG-CF, TPU, PVA, BVOH, PCTG) can be mixed with PP with careful chamber temperature management to avoid softening the low-temp material.

Support interfaces. PP's poor adhesion to other materials makes it an excellent breakaway support interface in some pairings; in the reverse direction, PCTG and HIPS can serve as breakaway interfaces for PP. PPprint's P-support 279 is a dedicated PP-compatible breakaway support that pairs with P-filament 721. **Multi-material buffer systems**: long multi-curve filament paths in filament buffers (AMS-style enclosures, MMU buffers, side-mounted spool holders with PTFE routing) increase retraction-induced stringing and filament drag, both of which PP tolerates poorly. Fiber-filled PP can wear internal buffer components on systems not designed for abrasive materials; check that the buffer system documentation lists fiber-filled material support before running PP-CF or PP-GF through it.

11.10 Application selection guide

Application	Recommended grade	Rationale
Living hinges, snap-fit lids	Unfilled PP copolymer	Only unfilled PP retains >100% elongation for repeated flex
Chemical containers, lab equipment	PP-GF or PP-CF	Chemical resistance from base; fiber for dimensional stability
Drone airframes, RC aircraft	PP-CF	Lowest density of any structural FFF filament; impact-resistant
Watertight bottles, single-wall	Unfilled PP (Centaur, UltiMaker, Fillamentum)	Translucency and food contact possible; single-wall vase mode reliably watertight
Automotive trim, under-hood (non-engine)	PP-GF or PP-CF	Thermal stability adequate; chemical resistance to oils, fuels, cleaners
Orthotics, prosthetics	PPprint 721, Fillamentum 2320	Biocompatible (PPprint), food-contact (Fillamentum); flexibility for wearable
Tooling, fixtures, jigs	PP-CF or PP-GF	Cost-effective alternative to PA-CF or PC; lighter than ABS/PETG fixtures
Electrical insulation	Unfilled PP	High dielectric strength; low water absorption; low cost
High-temperature structural (>90 °C)	Not recommended	PP HDT misleading; creep above 70 °C; switch polymer family

Table 11.4 — PP application selection. The right PP variant depends primarily on whether flexibility (forces unfilled) or dimensional stability (forces fiber-filled) is the binding constraint.

12. Polyethylene (PE) and other polyolefins

Polyethylene as an FDM filament is a much smaller market than polypropylene. The fundamental issues are similar — low surface energy, high crystallization shrinkage — and the solutions are similar (PE-on-PE build surfaces, fiber reinforcement) but the commercial filament options are sparse. HDPE in particular has been historically difficult in FFF due to warping and voiding; published work demonstrates parameter strategies to improve mechanical performance and surface quality, but the practical reality is that PE is rarely the right answer when PP is also available.

12.1 HDPE (high-density polyethylene)

Spectrum Filaments offers HDPE specifically as a filament; Braskem FL300PE is another documented option. Density ~0.95 g/cm^3, T_m ~130 °C, Vicat ~125 °C. Print at 210–230 °C extrusion temperature. Bed adhesion follows PP-class strategies: PE-coated sheet, packing tape, or specialty adhesive. Chemical resistance is excellent (similar envelope to PP); UV resistance is poor without carbon-black loading; food contact compliance depends on the specific grade.

12.2 PE filament applications

Watertight containers, chemical bottles, fuel-resistant components (PE swells less than PP in aliphatic hydrocarbons), pipe fittings as functional prototypes. PE is the obvious choice where PP-grade chemistry is wanted but the application benefits from PE's specific resistance profile — typically food and water containers in cold-chain applications, or aggressive alkaline environments where PP creeps over time. For most applications where the user is considering PE, PP is the practical default; PE is a small-niche material.

12.3 Other polyolefins: EVA, COC, COP

EVA (ethylene-vinyl acetate) appears in some flexible-foam filament niches; it bridges into TPU territory and is treated in Chapter 16. **Cyclic olefin copolymer (COC)** and **cyclic olefin polymer (COP)** are clear, low-moisture-absorption polymers used in medical and optical applications; available as filament from a few specialty vendors but essentially absent from the consumer market. Both are amorphous, print at 240–280 °C, and require PEI or polyolefin-compatible bed strategies depending on the specific grade.

Part VI

Polyamides

The polyamide family in FDM splits cleanly into two tiers: aliphatic nylons (PA6, PA66, PA12, PA612, PA11) — the classic engineering filaments where the dominant variable is moisture; and the semi-aromatic PPA family — where higher T_g, higher HDT, and an order-of-magnitude reduction in moisture sensitivity come at the cost of narrower processing windows and active chamber requirements.

13. Aliphatic nylons (PA6, PA66, PA12, PA612, PA11)

Aliphatic nylons are the original engineering thermoplastics — repeating amide (–CO–NH–) linkages along an otherwise aliphatic backbone, semi-crystalline, with mechanical envelopes that span from PA6's stiff-and-strong-when-dry through PA12's stable-but-modest to the toughness of PA11. In FDM the dominant variable is moisture: the same hydrogen-bonding network that gives nylons their stiffness and crystallinity makes them hygroscopic to a degree that materially changes every process and property number in this chapter. Drying is mandatory, not optional.

13.1 Chemistry and the dominant subtypes

Nylons are named by the carbon count of the monomers. **PA6** is the homopolymer of caprolactam — a single six-carbon repeating unit. **PA66** polymerizes hexamethylenediamine with adipic acid — a six-carbon diamine and a six-carbon diacid. **PA12** is the homopolymer of laurolactam, a twelve-carbon ring. **PA612** condenses hexamethylenediamine with twelve-carbon dodecanedioic acid. **PA11** is the homopolymer of 11-aminoundecanoic acid, derived from castor oil. The carbon count drives the headline property differences: more carbons between amide groups means lower amide density, which means lower moisture uptake, lower melting point, and lower bulk stiffness — but better dimensional stability in humid service.

Co-polyamides (CoPA) — random copolymers blending two or more nylon chemistries, most commonly PA6/PA66 — sit between their parent grades on every axis. CoPA filaments are the most common entry-level nylon SKU in the consumer market and are often what is meant by an unbranded "Nylon" listing.

Polymer	Repeat unit	T_m (°C)	Sat. moisture (%)	Position in FDM
PA6	caprolactam (C6 amide)	215–225	~8–10	Strong, stiff, dry; high moisture sensitivity
PA66	HMDA + adipic acid (C6+C6)	255–265	~6–8	Higher T_m than PA6; rare in filament because T_m pushes the process window
PA12	laurolactam (C12 amide)	175–180	~1.5	Dimensional-stability default; lower mechanical envelope than PA6
PA612	HMDA + DDDA (C6+C12)	210–220	~3	Balance: PA12-like moisture, PA66-like stiffness
PA11	11-aminoundecanoic acid (C11)	180–190	~1.9	Toughness-leading; bio-sourced; rare in unfilled filament
CoPA	PA6/PA66 random copolymer	195–215	~5–8	Entry-level; most generic "Nylon" filaments; cosmetic and prototyping

Table 13.1 — Aliphatic nylon subtypes in commercial FDM filament. The moisture column reports saturation uptake (full immersion / 100% RH equilibrium) per resin TDS data, not printed-part data and not the much lower 50% RH equilibrium value — for PA6 the two differ by roughly 3–4× (saturation ~8–10% vs ~2.5–3% at 50% RH). Printed specimens pick up moisture faster (more surface area, layer-line porosity) but reach similar saturation levels. Skip this table at your peril: matching the wrong subtype to a humid service environment is the most common failure mode in nylon FDM, well ahead of any print-parameter mistake.

13.2 The moisture problem

The polyamide hydrogen bond is what makes nylons strong and what makes them absorb water. Water molecules insert between amide groups, plasticize the polymer (lowering T_g), reduce stiffness, and increase elongation. The effect is large: PA6 equilibrated at ordinary room humidity loses roughly 60% of its bending modulus relative to its dry state, and its T_g can shift from ~55 °C dry to below room temperature wet. PA12 and PA612, with lower amide density, show much smaller swings (15–35% modulus loss at the same humidity-conditioned state). This is the most important property axis in selecting an aliphatic nylon and is the principal reason the PPA family (Chapter 14) exists at all.

Three practical consequences. **First**, every nylon TDS quotes "dry as-molded" values unless explicitly labeled as conditioned; planned service should derate those by the appropriate humidity-conditioned factor — using the equilibrium value for the expected service humidity, or the saturation value where the part will be immersed or run continuously wet — unless it will operate in low humidity. **Second**, filament that has equilibrated with room air will print poorly — the water flashes to steam in the melt zone, producing surface roughness, stringing, micro-bubbles in the bead, and severe layer-adhesion loss. Active drying before printing is mandatory; see §3.5 for the drying-protocol table. **Third**, post-print conditioning can be exploited deliberately: a PA6 part conditioned to equilibrium in a controlled humid environment trades stiffness for impact toughness and is more dimensionally stable thereafter than the as-printed dry part. Conditioning is a deliberate engineering step in some industrial nylon workflows; the resulting dimensions and mechanical envelope must be characterized empirically.

13.3 Property envelope

The table below collects typical FDM-printed values across the dominant aliphatic nylons. Where vendor TDS quote dry-as-printed and wet-conditioned values both, both are shown — the gap is the single most useful number on the page.

Polymer	T_g dry (°C)	HDT @ 0.45 MPa (°C)	Tensile (MPa)	Modulus (GPa)	Modulus loss dry→wet
PA6	~55	~155	70–85 dry / 40–55 wet	2.0–3.0 / 0.8–1.5	~60%
PA66	~70	~190	75–90 dry / 50–60 wet	2.5–3.5 / 1.5–2.0	~40%
PA12	~45	~145	45–55 dry / 40–50 wet	1.1–1.5 / 1.0–1.3	~15%
PA612	~50	~150	50–60 dry / 45–55 wet	1.4–1.8 / 1.2–1.6	~25%
PA11	~45	~150	50–65 dry / 45–55 wet	1.0–1.4 / 0.9–1.3	~20%
CoPA (PA6/66)	~55	~150	55–70 dry / 35–50 wet	1.6–2.4 / 0.8–1.4	~45%

Table 13.2 — Aliphatic nylon FDM property envelope. Dry values are as-printed in a ≤15% RH environment; wet values are conditioned to equilibrium at ~23 °C, 50% RH (not full saturation, which would be more severe). The dry-to-wet gap is the engineering signal: PA12 and PA11 are the right choices for parts that will see uncontrolled humidity in service. Confusing dry-only TDS values with field performance is the most common over-promising error in nylon part design.

13.4 Reinforced grades (PA-CF, PA-GF)

Carbon and glass reinforcement dominate the commercial nylon filament shelf. Chopped fiber at 10–25 wt% does three things at once: it raises stiffness by 2–4×, suppresses crystallization shrinkage (because fibers do not crystallize and physically restrain the matrix; see §3.2), and reduces moisture-driven modulus loss in absolute terms because the fiber stiffness is unchanged by water. The cost is brittleness — notched Izod typically drops 60–90% from the unfilled matrix value — and abrasive wear on every contact surface from the extruder gear through the nozzle bore. Hardened nozzles are mandatory; PCD or ruby tips extend useful life from hundreds to thousands of print hours under heavy fiber loading (see §4.1).

CF and GF are not interchangeable. Carbon fiber gives the highest specific stiffness, the lowest density (PA6-CF20 prints at ~1.15 g/cm^3 vs unfilled PA6's 1.13), and a characteristic matte black surface. Glass fiber is roughly half the stiffness gain at lower cost, in any color, with substantially better impact retention. For parts where stiffness-to-weight is the binding constraint (drone frames, end-effector tooling), CF wins. For impact-loaded brackets, snap-fit housings, or colored parts, GF is the better trade. Both reduce the moisture gap relative to the unfilled matrix but do not eliminate it: a PA6-CF part still loses substantial wet-state modulus, just from a higher dry starting point. This is the empirical observation that drove the development of PPA-CF — covered in Chapter 14.

13.5 Print process and calibration

Aliphatic nylons share a process envelope at the upper end of Tier 2 hardware (see §4): nozzles 240–290 °C, beds 60–110 °C, passive enclosure beneficial, active chamber not strictly required for the dimensionally stable grades (PA12, PA612, PA11) but recommended for PA6 and PA66 on parts over ~80 mm. Bed adhesion strategy is the second-most-important variable after drying.

Parameter	PA6 / PA66	PA12 / PA612	PA11	PA-CF / PA-GF
Nozzle (°C)	260–280	245–275	245–270	265–295
Bed (°C)	90–110	70–90	60–85	90–110
Chamber	passive 40–50 °C	open OK	open OK	passive 40–50 °C; active 55 °C for large parts
Part cooling (%)	0–10	0–20	0–20	0–10
Max volumetric (mm^3/s)	8–12	8–14	8–12	6–10
Pressure advance	0.030–0.06	0.025–0.05	0.025–0.05	0.04–0.08
Nozzle hardness	brass OK	brass OK	brass OK	hardened mandatory; PCD/ruby preferred
Drying	80–90 °C, 10–16 h	70–80 °C, 8–12 h	70–80 °C, 8–12 h	90–110 °C, 8–10 h
Bed surface	G10 garolite, or PEI + PVP / glue	smooth PEI; G10 acceptable	smooth PEI; G10 acceptable	G10 garolite; PEI + Magigoo PA or PVP

Table 13.3 — Aliphatic nylon process parameters (0.4 mm nozzle starting points). Per-spool calibration on the actual machine is mandatory; the values above are the starting points the polymer chemistry dictates. Skipping the drying row is where most first-time nylon prints fail before any other parameter has a chance to be wrong.

Bed adhesion deserves a paragraph. G10 garolite is the engineering default for PA6, PA66, and any high-warp CF-reinforced nylon: it grips strongly during the print and releases cleanly on full cool-down, with effectively no wear on the garolite sheet. Smooth PEI works for PA12, PA612, and PA11 (lower shrinkage, lower grip needed) and for short prints of PA6 over a glue-stick release layer. Textured PEI is acceptable for PA12-family materials but tends to over-grip PA6 and damage the sheet on removal. Magigoo PA is the dedicated adhesive in the Magigoo family for the nylon class. CryoGrip Glacier — a frost-effect engineered sheet — has been documented as a stable cold-release surface for CoPA at moderate bed temperatures and worth knowing about for prints where standard garolite-on-magnet stacks aren't available.

13.6 Brand landscape

The aliphatic nylon market has consolidated around a handful of vendors with well-documented engineering-grade SKUs.

Brand / line	Notable SKUs	Distinguishing notes
Polymaker Fiberon	PA6-CF20, PA612-CF15, PA6-GF25, PolyMide CoPA	Engineering line built on documented resin grades; 20% CF in PA6-CF20 gives ~8.6 GPa Young's modulus; PA612-CF15 is the practical choice when wet-state retention matters more than maximum stiffness. CoPA targets entry-level nylon use.
Bambu Lab	PA6-CF, PA6-GF, PAHT-CF, PA-CF Support	PAHT-CF is PA12-based (not PPA — see §2.3 and Ch 14); PA6-CF and PA6-GF compete directly with Fiberon. Spool-deformation risk in dryers at the upper drying-temperature range.
3DXTech CarbonX	PA6 + CF, PA12 + CF, Nylon X family	US industrial line; ISO 9001 manufacturing; rigorous published TDS data; price 1.5–2× consumer-tier equivalents.
Prusament	PA11-CF Carbon Fiber	PA11-CF is rare in the consumer market; bio-sourced PA11 matrix gives the impact-toughness leader among reinforced nylons.
Overture	Easy Nylon (CoPA)	CoPA matrix at consumer prices; entry-level toughness; CryoGrip Glacier validated as a compatible build surface.
Siraya Tech	NylonPro CoPA, Mecha PA6-CF	Mainstream consumer pricing; broad color availability on the unfilled CoPA SKU.
Fiberlogy	Nylon PA12, PA12 + GF	European mainstream; PA12 unfilled in multiple colors; modest mechanical envelope but reliable printing.
eSun, Creality, Sunlu	Generic "Nylon" SKUs (CoPA or PA6 base)	Budget tier; specifications often incomplete; suitable for prototyping where mechanical performance is not on the spec sheet.

Table 13.4 — Aliphatic nylon brand landscape (early 2026). The Polymaker Fiberon line and the Bambu PA-CF / PA-GF / PAHT-CF line are the two most thoroughly documented consumer-accessible product families; 3DXTech CarbonX is the default where industrial qualification is in scope. Cross-brand substitution within a polymer subtype (PA6-CF from Brand A vs Brand B) is not free — fiber loading, matrix grade, and sizing chemistry all shift the printed envelope by 10–25%.

13.7 Reading datasheet figures critically

The TDS values collected in Table 13.2 are the right starting point for material selection, but they are not what a printed part will deliver. Independent testing of aliphatic-nylon filaments on controlled, uniform equipment consistently lands below the manufacturers' published numbers, and for this polymer family the shortfall is large enough to change design decisions. This section explains why the gap exists and how to design around it; it deliberately quotes no third-party measured figures, because the reliable independent datasets in this space are published under their owners' terms (see Appendix D.1).

One point of method matters first. Vendors publish two stiffness numbers: a Young's (tensile) modulus and a bending (flexural) modulus, and the headline marketing figure is usually the tensile one - Polymaker's widely quoted "8.6 GPa" for PA6-CF20 is Young's modulus, not flexural. A bending test measures the flexural modulus, so any honest comparison against a bending result must use each datasheet's flexural-modulus figure (ISO 178), XY orientation, dry state — not the larger tensile headline. Mixing the two is a common way to manufacture an apparent agreement, or an apparent scandal, that is really just a units mismatch.

Published bending modulus overstates printed stiffness, and for aliphatic nylons the gap can approach a factor of two. Two effects compound. The first is general to all filled filaments and is the same one §14.11 identifies for polyphthalamides: datasheet modulus is derived from optimally printed, fully dense specimens, while a real part carries layer-line porosity and imperfect fiber alignment. The second is specific to nylons - they are hygroscopic, and unless a specimen is printed bone-dry and tested immediately, absorbed moisture plasticizes the matrix and drops the modulus further. A datasheet specimen is a best case on both counts; a part printed and handled normally is not. The engineering consequence: for aliphatic nylons, do not treat published bending modulus as a 20-30% over-estimate the way one might for a less moisture-sensitive polymer - treat it closer to a ceiling, and design from a conservatively derated value confirmed on your own machine.

Heat figures diverge by method, and unlike modulus they do not err consistently in one direction. Datasheet HDT (ISO 75, a defined-deflection test under a fixed load) and the deformation-temperature tests used by independent reviewers are different procedures, so the two are not expected to match, and observed differences are method variance rather than evidence that a vendor is overstating. The practical lesson is simply that a lone heat number on a datasheet means little without knowing the test behind it. For service-temperature decisions, the continuous-service guidance in Appendix A and the application-fit discussion in §13.8 - built from T_g and HDT together - is a sounder basis than any single published figure.

Brand still moves the result. Two filaments sold under the same nominal class - say, PA6-CF from two different makers - can rank one way on their datasheets and the opposite way once printed and measured. This is the cross-brand variance §13.6 flags: fiber loading, matrix grade, and sizing chemistry shift the printed envelope enough that datasheet stiffness is not a reliable way to rank two products from different manufacturers. Where a vendor reports flexural modulus honestly as an orientation-dependent range rather than a single number - Prusament does this for PA11-CF - that range is itself the most accurate thing the datasheet says about printed stiffness, and no single headline figure should be expected to replace it.

13.8 Application fit

Aliphatic nylons are the right choice when the part will see mechanical loading at modest temperature (under ~80 °C continuous), the service environment is dry or controlled humidity, and the failure mode of interest is fatigue or wear rather than impact spike. Iglidur-class PA6 grades engineered for tribological service are the canonical wear-bearing application. Drone components and end-effector tooling are the canonical CF-reinforced applications. Cable-management housings and ergonomic grips are the canonical CoPA/PA12 applications.

Aliphatic nylons are the wrong choice when the service environment is uncontrolled humidity and the design depends on stiffness — the modulus loss is catastrophic for PA6 and substantial for PA612 and PA11. PPA (Chapter 14) is the engineering answer to that constraint, at a cost premium and a process-discipline premium. Aliphatic nylons are also the wrong choice when continuous service exceeds 100 °C: PA11 and PA12 creep above their T_g; PA6 holds shape better but loses too much modulus from the moisture interaction. Above 100 °C continuous, the appropriate options are PPA, PC blends with high-PC content (Chapter 15), or - at the high-performance tier - PPS or PEI (Chapter 18).

14. PPA / semi-aromatic polyamides — deep dive

Polyphthalamide (PPA) is a semi-crystalline, semi-aromatic polyamide: the same amide backbone as the aliphatic nylons of Chapter 13, but with one of the monomers — typically the diacid — replaced by an aromatic ring (terephthalic or isophthalic acid). In its neat industrial resin form the aromatic ring stiffens the chain substantially, raising the glass transition and melting point well above PA6 — the PA6T, PA9T, and PA10T chemistries of Table 14.1 melt between 290 and 325 °C — and reducing saturated moisture absorption to roughly one-fifth of PA6's value. The printable PPA filaments this chapter surveys, however, are not those neat high-temperature resins: to be extrudable on prosumer hardware they are printability-modified copolymers with a markedly lower melting point (commonly 230–260 °C) and a glass transition near 80 °C, while keeping most of the moisture-resistance advantage. The reader should hold both facts at once — PPA the resin class is a high-temperature family, but PPA the filament is a moderate-temperature, low-moisture engineering material. The trade for the filament is still a narrower processing window than the aliphatic nylons, active-chamber requirements, hardened-nozzle requirements for the reinforced grades (which is essentially all commercial PPA filament), and a price premium of 2–4× over equivalent aliphatic PA-CF.

14.1 Chemistry: the PPA subtype family

"PPA" is an umbrella for several specific semi-aromatic polyamide chemistries, distinguished by the aliphatic diamine paired with the aromatic diacid. The subtype determines the melting point, moisture uptake, and bio-content; filament manufacturers rarely disclose which is in the spool.

Subtype	Monomers	T_m (°C)	Saturated moisture (%)	Commercial position
PA6T/X	hexamethylenediamine + TPA, copolymerized (e.g. PA6T/66, PA6T/6I, PA6T/DT)	~290–320	~2–3	Dominant industrial PPA chemistry; underlies DuPont Zytel HTN and many compounded filaments. Pure PA6T melts above its decomposition temperature so it always ships as a copolymer.
PA9T	nonanediamine + TPA	~306	~0.17	Kuraray Genestar® flagship; the lowest-moisture PA in commerce; rare in third-party filament.
PA10T	decanediamine + TPA	~316	~0.4	Partly bio-sourced (decanediamine from castor oil); between PA6T and PA9T on every axis.
PA4T	butanediamine + TPA	~325	~1.5	Newer chemistry, industrialized by DSM; high T_m pushes processing to the very top of Tier 3 hardware.

Table 14.1 — PPA subtype family. Filament TDSs almost never identify which subtype is in the spool; subtype-level identification is generally only possible through DSC analysis or via inference from the reported T_m. Treat the "PPA" label as a chemistry family rather than a single material when comparing spools across vendors.

14.2 PPA vs aliphatic nylons: the four axes that matter

Compared head-to-head with the aliphatic nylons of Chapter 13, PPA wins on heat resistance, moisture stability, dimensional stability under load, and wet-state mechanical retention; aliphatic nylons win on printability, cost, and unfilled toughness. The wet-state-retention gap is the headline.

Property	PA6	PA12	PA612	PPA filament (a)
T_g (°C)	~55	~45	~50	~80
HDT @ 0.45 MPa (°C)	150–170	140–150	150–160	80–200
Saturated moisture (%)	~8–10	~1.5	~3	~1–2.6
Stiffness loss dry→wet	60%	15%	25%	~2–3%
Print temp (°C)	260–280	245–275	255–280	280–320
Active chamber	optional	optional	optional	recommended (55–65 °C)
Relative filament cost	$	$$	$$	$$$

Table 14.2 — PPA vs aliphatic nylons. (a) The PPA column gives FDM filament-grade values: the printable PPA filaments surveyed in this chapter are printability-modified semi-aromatic copolymers with a glass transition near 80 °C, not the neat high-temperature PA6T/PA9T resins of Table 14.1, whose T_m sits at 290–325 °C. The HDT range spans unfilled PPA (~80 °C at 0.45 MPa) through annealed PPA-CF (~190–200 °C at 0.45 MPa); see Table 14.5 and Appendix A. The single most consequential row is the fourth: PPA-CF retains the large majority of its dry-state stiffness in humid service, where PA6-CF loses about three-fifths of its bending modulus. The exact wet-retention figure is grade-specific — the near-total retention seen in the Table 14.6 measurements is a Bambu PPA-CF result, not a family constant — but the direction holds across PPA grades. For automotive under-hood parts, outdoor enclosures, and any structural application with uncontrolled humidity, this gap becomes the engineering case for paying the PPA cost premium.

14.3 The PAHT / HTN / PPA labeling problem

Part I §2.3 introduced the marketing mess: "PAHT" (Polyamide High-Temperature) originally referred to PPA-based filaments around 2020–2022 but has been applied across at least four distinct base polymers. "HTN" (High-Temperature Nylon), used by 3DXTech for the CarbonX HTN+CF product line, is functionally synonymous with PPA at the chemistry level — both refer to semi-aromatic polyamides. The DuPont Zytel HTN trade family is similarly a PPA product line (specifically PA6T copolymers). This chapter consolidates what's known about what each PAHT label actually contains.

Filament product	Actual base resin	Source / evidence
Siraya Tech Fibreheart PAHT-CF (pre-2024)	PPA	Rebranded to Fibreheart PPA-CF in late 2024 by the manufacturer; chemistry never changed.
Bambu Lab PAHT-CF	Modified PA12	Distinct from Bambu Lab PPA-CF, which is true polyphthalamide. Both products are sold concurrently.
BCN3D PAHT CF15	Modified high-temperature PA (proprietary)	BCN3D does not publish the base polymer; mechanical envelope places it between PA6-CF and PPA-CF.
Qidi PAHT-CF / PAHT-GF	PPA	Packaging explicitly carries "(PPA-CF)" or "(PPA-GF)" parenthetically.
Generic Asian-market PAHT-CF	Modified PA6 or PA6/66 copolymers	Inferred from mechanical envelope and price; varies spool-to-spool.

Table 14.3 — What "PAHT" actually means by vendor (as of early 2026). The filament technical datasheet, not the SKU name, is the only reliable identifier of underlying chemistry. The industry trend since the mid-2024 Bambu PPA-CF launch has been toward explicit "PPA" naming; the legacy PAHT spools continue to circulate in distribution and on retail shelves.

14.4 Reinforcement variants: unfilled, CF, CF-Core, GF

PPA reaches commercial FDM filament in four reinforcement configurations. Carbon-fiber variants dominate shelf space because PPA's strong warp tendency (driven by its high crystallinity, similar to PA6) is largely tamed by fiber reinforcement, where the unfilled grade requires substantially more process discipline. Unfilled PPA is rarer and is currently most accessibly supplied by Siraya Tech Fibreheart PPA.

Form	Typical loading	Best for	Avoid for
Unfilled PPA	0%	Wear surfaces, gears, parts requiring impact toughness in addition to heat resistance; tappable threads	Large flat parts (warp without fiber restraint); high-tolerance dimensional work
PPA-CF	10–25 wt% chopped CF	Structural brackets, drone frames, end-effector tooling, automotive under-hood, jigs and fixtures	Cyclic flexural loading (CF creates fatigue-failure planes); tight-tolerance parts unless annealed and conditioned
PPA-CF Core	25% CF (concentrated in filament core), pure-PPA shell	PPA-CF applications where Z-axis layer adhesion is the binding constraint	Multi-material printers requiring uniform filament cross-section; cost-sensitive prints
PPA-GF	10–20 wt% chopped GF	Structural parts where color matters, snap-fit and hinge geometry where CF brittleness causes failures, electronics housings	Maximum stiffness applications (CF wins on modulus); lowest cost (CF and GF are price-comparable)

Table 14.4 — PPA reinforcement variants. CF-Core is a co-extruded skin-core architecture: a pure-PPA outer shell that promotes Z-axis bonding with itself from layer to layer, around a CF-rich core that carries the in-plane mechanical load. Mixing variants in a single multi-material print risks chamber-compatibility issues (see §14.10).

14.5 Brand-by-brand property envelope

The table below consolidates published TDS values across the major brands for direct comparison. Values are XY-direction tensile and flexural data from each manufacturer's published datasheet — these are not from a unified independent test. Use them as relative indicators; §14.11 explains why these published figures should be read as a ceiling rather than an expectation.

Brand · product	Tensile (MPa)	Flex mod. (GPa)	HDT (°C)	Reinforcement
Siraya · Fibreheart PPA (unfilled)	72	3.4	81 (0.45 MPa)	0%
Siraya · Fibreheart PPA-CF	98	7.4	192 (0.45 MPa, anneal)	15% CF
Siraya · Fibreheart PPA-CF Core	121	9.5	199 (0.45 MPa, anneal)	25% CF (core)
Bambu Lab · PPA-CF	168	~10	227	~15–20% CF
Bambu Lab · PAHT-CF (PA12-based)	90	~4	194	~15% CF
3DXTech · CarbonX HTN+CF	130	~9	~195–240	15–20% CF
3DXTech · FibreX PPA+GF15	115	~7	260	15% GF

Brand · product	Tensile (MPa)	Flex mod. (GPa)	HDT (°C)	Reinforcement
Raise3D · Industrial PPA CF	120	~7	~210	15% CF
Qidi · PAHT-CF	110	6.9	~200	15% CF
Qidi · PAHT-GF	85	~5	~180	15% GF
Flashforge · PPA-CF (LUVOCOM)	—	~6	220	10% CF

Table 14.5 — PPA filament property envelope (2024–2026 TDS values). HDT is load- and anneal-state dependent and not reported on a single basis by every vendor; where a vendor publishes multiple figures the table gives the 0.45 MPa value with the anneal state noted, and a brand's own datasheet should be consulted for the 1.80 MPa figure. The Bambu Lab PPA-CF flex-modulus figure of ~10 GPa is roughly twice the consumer-tier average, reflecting both higher fiber loading and process-tuned compounding; the price ratio of ~4× over equivalent-chemistry Siraya Fibreheart PPA-CF is real and material to procurement. Wet-state values vary substantially and are documented separately in §14.6 for products where vendors publish them.

14.6 Brand survey

Siraya Tech (Fibreheart). Siraya offers the broadest PPA range accessible to consumers. The line consists of Fibreheart PPA (unfilled — originally sold as Fibreheart PAHT), Fibreheart PPA-CF (15% chopped CF, also originally PAHT-CF), and Fibreheart PPA-CF Core (25% CF in a co-extruded core with a pure-PPA shell, launched late 2024). The CF Core product specifically targets the higher-priced tier with what Siraya argues is superior Z-axis layer adhesion through its skin-core architecture. Pricing sits at roughly one-quarter the per-kilogram cost of the highest-priced PPA-CF on the market for nominally equivalent chemistry. Fibreheart PPA is the most accessible unfilled true-PPA filament in the consumer market.

Bambu Lab. Bambu launched its PPA-CF in mid-2024 at a price premium positioned for industrial qualification work. The product TDS publishes the dry/wet property comparison that quantifies PPA's headline value proposition — Table 14.6 below — and is one of the few PPA TDS to do so explicitly. A companion PPA-GF was added in late 2025 / early 2026. Note that Bambu sells two distinct products with similar names: Bambu PAHT-CF (PA12-based) and Bambu PPA-CF (true polyphthalamide); they are not the same filament. PAHT-CF remains in the lineup as a budget option roughly half the cost of true PPA-CF.

Property (XY direction)	Normal PA6-CF	Bambu PA6-CF	Bambu PAHT-CF	Bambu PPA-CF
Bending modulus, dry (MPa)	4,870	5,460	4,230	9,860
Bending modulus, wet* (MPa)	1,890	3,560	3,640	9,620
Stiffness decline dry→wet	61.2%	34.8%	13.9%	2.4%
Bending strength, dry (MPa)	141	151	125	208
Bending strength, wet* (MPa)	67	95	115	202
Strength decline dry→wet	52.5%	37.1%	8.0%	2.9%
Max use temperature (°C)	—	—	194	227

*Table 14.6 — Bambu Lab PPA-CF Technical Data Sheet V1.0, XY tensile/flexural bars, 100% concentric infill. *Wet = sample conditioned to equilibrium at ~25 °C, 55% RH (an in-service humidity state, not full immersion saturation). The 2.4% stiffness decline and 2.9% strength decline for Bambu PPA-CF wet-vs-dry are the empirical case for PPA over PA6-CF in any*

humidity-exposed application; the 60%+ decline for unfilled-matrix PA6-CF is the principal failure mode this chapter exists to document.

3DXTech (CarbonX, FibreX). The Grand Rapids, Michigan industrial line with the longest continuous history of PPA filament production. ISO 9001:2015 manufacturing; HTN terminology rather than PPA in product names but the chemistry is the same family. CarbonX HTN+CF reports T_g 125 °C and thermal resistance to ~240 °C (higher than ULTEM 9085 PEI on the relevant axis); FibreX PPA+GF15 reports HDT 260 °C and T_m 305 °C. Prices run 1.5–2× consumer equivalents; this is the default choice when parts will see qualification testing.

Polymaker (Fiberon line — notable absence). Polymaker's Fiberon engineering line is one of the most refined high-temperature filament product families on the market, but as of early 2026 it does not include a true PPA filament. Polymaker has targeted the PPA application space with PA6-CF20 (metal-replacement positioning at moderate cost — see Ch 13 §13.6) and PPS-CF10 (ultra-high-temperature, flame-retardant — Ch 18). The absence of a true PPA-CF leaves a gap that competitors have actively filled. Polymaker typically backfills engineering-resin gaps on a 12–24 month cadence.

Raise3D, Qidi, Flashforge, BCN3D. Raise3D's Industrial PPA CF (15% CF) and PPA GF (15% GF) are sold primarily for their industrial printer line, with a PPA breakaway support filament as a companion product — a useful niche, since most vendors leave PPA users to figure out supports independently. Qidi sells PAHT-CF and PAHT-GF (both PPA-based, with PPA labeling parenthetically on the packaging) at budget pricing; Flashforge uses LUVOCOM® PPA-CF (Lehvoss compound) with 10% CF, reporting HDT 220 °C and unusual non-heated-chamber compatibility for a PPA. BCN3D's PAHT CF15 is shipped primarily for their industrial printer family; the base polymer is undisclosed but the mechanical envelope places it between PA6-CF and PPA-CF.

14.7 Print process and calibration

PPA's narrow processing window — driven by the high T_g and the steep viscosity drop above T_m — produces less brand-to-brand variation in recommended parameters than most polymer families. Starting points for 0.4 mm hardened-nozzle hardware:

Parameter	Unfilled PPA	PPA-CF	PPA-GF
Nozzle (°C)	275–310	280–320	285–320
Bed (°C)	80–110	90–120	90–120
Chamber	40–60 °C preferred	55–65 °C active recommended	55–65 °C active recommended
Part cooling fan (%)	0	0; 5–15% overhangs only	0; 5–15% overhangs only
Print speed (mm/s)	30–60	30–80	30–80
Max volumetric (mm^3/s)	7–9	8–12	8–12
Nozzle hardness	hardened or brass OK	hardened steel mandatory	hardened steel mandatory
Nozzle diameter (mm)	0.4+	0.4+ (0.6 preferred)	0.4+ (0.6 preferred)
Bed surface	smooth PEI + glue stick / PVP / Magigoo PC	smooth PEI + glue stick / PVP / Magigoo PC; G10 garolite acceptable	smooth PEI + glue stick / PVP

Table 14.7 — PPA starting print parameters. The chamber row is the line between marginal and consistent: passive enclosures will print small PPA-CF parts but interlayer bonding falls off above ~80 mm Z-height as the upper-layer temperature drops below the crystallization-onset window. Active chamber is the engineering fix; see §4.3.

14.8 Drying protocol

PPA filament moisture uptake is grade-dependent: always far below PA6, and ranging from PA12-class to somewhat higher depending on formulation and reinforcement — the carbon-fiber grades sit at the low end, unfilled PPA somewhat above. Moisture symptoms in PPA prints are characteristic: fine stringing despite well-tuned retraction, surface roughness, oozing during travel moves, and — the structural failure mode — micro-bubbles in the wall bead that destroy Z-axis layer adhesion at internal interfaces invisible from the surface.

Drying guidance for PPA varies more by brand than for most filament families, and the chapter's Part I cross-reference should be read as the conservative end of a range rather than a universal requirement. The Part I drying-protocol table (§3.5, Table 3.1) specifies PPA at the high end — up to 100–140 °C for 8–12 hours — which matches Bambu's guidance for its higher-melting PPA-CF and suits the engineering PPA grades; at that upper end a convection oven genuinely outperforms a filament dryer, since filament dryers top out around 80–90 °C in practice. Other current filaments specify a markedly milder protocol: Siraya Fibreheart PPA calls for 80–100 °C for 4–6 hours, and Siraya PPA-CF for 100 °C for 4–6 hours, with both treating drying as needed only when moisture symptoms appear or the vacuum packaging has been compromised. The practical rule is to follow the spool's own datasheet: an 80–90 °C filament dryer is adequate for the Siraya-class grades and for re-drying any opened spool, while the 100–140 °C oven schedule is reserved for the brands that specify it. The 160 °C upper limit on drying temperature is a spool-substrate limit, not a polymer limit — plastic spools deform above this point. Cardboard spools tolerate higher temperatures but introduce their own debris-shedding problems.

During the print itself: dry-box storage with active desiccant or active heat (low-end filament dryer running at 50–70 °C) is the practical standard. Re-dry any spool that has sat open for more than 24 hours before a serious print.

14.9 Annealing

PPA is semi-crystalline and responds well to annealing on the CF and GF variants: the treatment increases crystallinity, improves HDT and Z-axis strength, and reduces residual stress. Vendor schedules vary, with the more aggressive schedule belonging to Bambu PPA-CF (120–140 °C, 6–12 h). Most consumer PPA-CF responds well to 100–120 °C for 4–6 h with the part supported in packed sand or salt during the heat soak to prevent sag of fine features.

Unfilled PPA is the notable exception. Siraya Tech explicitly advises against annealing Fibreheart PPA — without fiber reinforcement the part warps during the heat soak, and the warp tendency carries through to the final part more than the crystallinity gain pays back in HDT. This is consistent with the Part I §3.6 framing: anneal CF and GF variants where warp is constrained; anneal unfilled PPA only on small, robust geometries where the warp risk is low to begin with.

14.10 Multi-extruder and abrasive-handling considerations

Two PPA-specific failure modes emerge on multi-extruder hardware that do not appear on single-extruder Tier 3 setups.

Filament brittleness inside the filament path. PPA-CF — especially at the higher fiber loadings — is brittle enough on the spool that bent filament paths can snap it inside PTFE tubes. PA6-CF tolerates this; PPA-CF does not. On hardware with a moving toolhead that flexes the filament tube as it returns to its home position, the tube bending angle near the toolhead is the failure point. Practical mitigations: route the filament through whichever toolhead experiences less tube-bending stress (typically the fixed-position rather than the lifting hotend on dual-hotend systems); rotate the PTFE tube 360° counter-clockwise and reinsert in a gentler spiral before printing PPA-CF; or feed the filament from a dry box mounted close to the toolhead to minimize the tube path length entirely. Vendor documentation on this point is concentrated in the printer-specific guides rather than the filament TDS.

Abrasive-nozzle compatibility with offset calibration. Hardened steel, ruby, tungsten carbide, and PCD-tipped (E3D Diamondback) nozzles are all engineered for the fiber-loaded PPA application. PCD tips are non-conductive and cannot be detected by inductive or eddy-current nozzle-offset sensors common on prosumer printers, requiring camera-based offset calibration instead; this is mentioned in §4.1 and becomes operationally relevant when switching from an aliphatic-nylon nozzle to a PPA-grade nozzle mid-spool.

Multi-material chamber compatibility. PPA-CF qualifies as a high-temperature filament in every vendor's compatibility scheme. It cannot be combined with low-temperature filaments (PLA, PETG, soft TPU) in the same print: the chamber and bed temperatures required for PPA-CF will soften and warp those materials. Compatible-tier filaments include other engineering-grade nylons (PA6-CF, PAHT-CF, PA-GF), ABS, ASA, PC blends, PET-CF, PPS-CF, and ABS-GF. Compatible support filaments are limited; PPA-specific breakaway supports (notably the Raise3D Industrial PPA breakaway line) and same-material soluble strategies are the practical options.

14.11 Reading datasheet figures critically

Every value in Table 14.5 comes from a manufacturer's datasheet. Independent testing of PPA-class filaments on controlled, uniform equipment shows those datasheet figures should be read with the same caution §13.7 applies to the aliphatic nylons. This section describes the patterns that recur across the PPA family without reproducing any third-party measured numbers; the reliable independent datasets in this space are published under their owners' terms (see Appendix D.1).

Flexural modulus is consistently overstated. Across PPA-class products, printed-part stiffness measures below the datasheet figure, and the gap tends to be widest on the highest claims. This is not specific to one brand: TDS modulus is typically derived from injection-molded or optimally-oriented specimens, while a printed part carries layer-line porosity and imperfect fiber alignment. Treat published modulus as a ceiling rather than an expectation, and derate it by roughly 20-30% for design - then confirm against a specimen printed and conditioned the way the real part will be.

Heat figures diverge by method, not always by direction. Datasheet HDT and the deformation-temperature tests used by independent reviewers load the specimen differently, so the two are not expected to match - a product can measure above its TDS heat figure on one test and below it on another without either number being wrong. The takeaway is that a single heat number on a datasheet means little without knowing the test behind it. For service-temperature decisions, the continuous-service guidance in Appendix A and the application-fit discussion in §14.12 - built from T_g and HDT together - is a sounder basis than any single published figure.

Diminishing returns above ~20% fiber loading. A pattern worth carrying into product selection, and consistent with the §14.6 discussion: once carbon-fiber loading rises past roughly 20%, measured stiffness tends to plateau while brittleness keeps increasing. A 25%-loaded grade does not reliably out-stiffen a well-made 20% grade in a printed part, so a higher headline loading on the datasheet is not by itself a reason to choose one PPA-CF product over another. As with the nylons, fiber loading, matrix grade, and sizing chemistry mean datasheet stiffness is not a dependable way to rank products from different makers; where independent data exists it is most useful as a cross-check on the relative ranking, not as a substitute for testing on your own machine.

14.12 Application fit

Choose PPA when: continuous service exceeds 100 °C and a reinforced grade is used (engine-bay brackets, manifolds, oven-adjacent fixtures — PPA-CF and PPA-GF carry the heat, while unfilled PPA filament tops out near its ~75–85 °C HDT and is not the grade for sustained high-temperature load); exposure to fuels, oils, glycols, or aggressive cleaners is expected (PA6 fails on chemical contact, PPA holds up); outdoor parts need to retain stiffness through winter humidity (PA6-CF loses >60% modulus wet, while in Bambu's published dry-versus-wet test its PPA-CF lost only ~2%); mechanical parts under load see wear, fatigue, or dimensional-stability requirements; strength-to-weight is the binding constraint (drone frames, end-effector tooling); under-hood automotive replacement parts are in scope.

Avoid PPA when: the part is aesthetic or cosmetic (PPA-CF is black-only with matte surface finish, and the cost is unjustified); service stays at room temperature (PETG, PCTG, or PA612 will print more reliably for the same mechanical envelope at one-third the cost); cyclic flex is required (CF reinforcement creates fatigue-failure planes; an unfilled engineering nylon - PA12, PA11 - or PCTG is more forgiving); the design is still iterating (the printability tax is real; a $200/kg material is a lot to spend on parts that may be revised 5-10 times before freeze).

Adjacent alternatives worth considering. PA612-CF15 captures most of the wet-state-retention benefit at lower cost and easier printing - a strong middle ground if PPA's full heat tier is not required. PA6-CF and PAHT-CF are appropriate when service temperature stays below 80 °C and cost matters. PPS-CF (Chapter 18) is the next tier up for parts seeing >200 °C continuous and is flame-retardant - a different polymer family, more demanding to print, but reaching temperatures PPA cannot. PEEK and PEKK (Chapter 19) are the tier above that, requiring Tier 4 hardware outside this volume's scope.

Part VII

Polycarbonates

Polycarbonate (PC) is the highest-T_g amorphous polymer routinely accessible at the consumer FDM tier — and the polymer most likely to be sold under a name that doesn't describe what's in the spool. Almost every "PC" filament is an alloy or composite, not pure polycarbonate; the engineering envelope and the processing window both depend on which.

15. PC and PC blends — deep dive

Polycarbonate (PC) occupies a specific niche in the FDM polymer hierarchy: amorphous, transparent in its pure form, with T_g ~145–150 °C, HDT around 135–145 °C at 0.45 MPa, tensile yield 60–70 MPa, and the highest notched impact resistance of any polymer in this volume's commodity-to-engineering range — neat PC notched Izod reaches the 60–85 kJ/m^2 band in ductile failure, several times that of PCTG and well above PETG (PC blends sit lower than neat PC but still lead the field). It is the engineering workhorse for parts that load at 100–130 °C in service — automotive under-hood brackets, electronics enclosures, optical mounts, structural components. The catch is that pure unmodified PC is rare in commercial FDM filament. The market divides into PC alloys (blended with another polymer at the resin level to reduce warp and shift mechanical balance) and PC composites (compounded with fibers, conductive additives, flame-retardant packages, or PTFE). Choosing between them is the entry-level skill for using "PC" in FDM; printing them well is the next-level skill.

15.1 Polycarbonate chemistry

BPA-polycarbonate (bisphenol-A polycarbonate) is the dominant chemistry — a thermoplastic polyester of carbonic acid condensed with the bisphenol-A diol. The bulky aromatic groups and the carbonate linkage produce a polymer that is amorphous (no crystallinity, full transparency in clear grades, no Schlieren texture), glass-like in mechanical character (high stiffness combined with substantial impact toughness), high-T_g, and processable from 280–320 °C in injection molding. Four global resin producers underlie essentially all commercial PC filament: Covestro Makrolon, SABIC Lexan, Mitsubishi Iupilon, and Trinseo Calibre. Filament TDS rarely identify the base resin; differences in molecular weight, additive packages, and (for alloys) the partner polymer account for most brand-to-brand variance in printed performance.

BPA itself is a regulated monomer with documented endocrine-disruption concerns at consumer-exposure levels. In finished polymer form only trace unreacted monomer remains, which is the relevant context for printed-part safety — effectively negligible for printed surfaces, but worth flagging for risk-communication purposes when end users ask. For applications where BPA is a regulatory or perceptual concern, Eastman Tritan (a TMCD-rich terpolymer marketed as a polycarbonate substitute, covered in Chapter 8) reaches PC-class hydrolytic stability and a similar HDT range without using BPA. Tritan-class resin carries food-contact certification at the resin level — but, as §8.9 stresses, that certification does not transfer to a printed part: FDM layer lines harbor contamination and hotend residue, so any food- or medical-contact use requires sealing and its own qualification regardless of the resin's pedigree.

15.2 The PC labeling problem (deepening §2.4)

Part I §2.4 introduced the principle: "PC" on a filament label is almost always an alloy or composite. The detail matters for procurement and process planning.

PC alloys blend PC with another polymer at the resin level. The partner polymer raises one property at the expense of another. **PC/ABS** is the dominant alloy: ABS lowers T_g and HDT, raises notched impact substantially (the butadiene phase absorbs energy), reduces warp during cooling, and lowers cost. The trade is well-balanced for general-purpose engineering work. **PC/PBT** is the second-most-common alloy: PBT is a semi-crystalline polyester; the alloy retains PC's stiffness and high T_g while adding chemical resistance and crystallinity-driven impact retention. The alloy carries a T_m value on its TDS (typically 220–230 °C from the PBT phase) where pure PC does not. **PC/ASA** combines PC's heat resistance with ASA's UV stability; relevant for outdoor parts but rare in commercial filament. **PC/PCTG** retains PC transparency and stiffness while adding PCTG's toughness; rare, and rarely announced.

PC composites compound PC with a filler or additive. **PC-CF** and **PC-GF** add stiffness and HDT at the cost of brittleness and abrasion. **ESD-PC** with conductive additives (carbon nanotubes or specialty carbon black) drops surface resistivity into the electrostatic-dissipation range. **FR-PC** with flame-retardant packages targets UL94 V-0 compliance. **PC/PTFE** with PTFE compounded in provides low-friction surfaces for wear applications.

Filament TDSs typically disclose "PC blend" (alloy with partner unnamed) or "PC + N% [filler]" (composite with the loading specified). The mechanical envelope, processing window, and printability all depend on which approach was used. Prusament PC Blend, Bambu PC, and PolyMax PC — the three most well-documented general-purpose PC products on the consumer market — are all alloys with undisclosed partner polymers; Polymaker's PC-ABS and PC-PBT, by contrast, name their alloy partners explicitly.

15.3 General-purpose PC blends

This is the consumer default for "I need PC behavior on prosumer hardware." Mechanical envelope: tensile yield 55–65 MPa (lower than pure PC's 65–70), T_g 105–150 °C depending on the alloy partner, HDT @ 0.45 MPa 95–145 °C. Print at 260–290 °C nozzle, 100–115 °C bed, enclosed chamber strongly recommended (passive 40–50 °C adequate for most parts up to ~150 mm; active chamber preferred above that). Brass nozzles wear acceptably on unfilled PC blends. The category includes:

Product	Class	T_g (°C)	HDT @ 0.45 MPa (°C)	Tensile yield (MPa)	Notes
Prusament PC Blend	PC alloy (partner not disclosed)	—	113	63	Most widely-documented consumer PC; published printed-specimen data
Bambu PC	PC (alloy-tuned for lower shrinkage)	145	112	55	Active chamber 45–60 °C specified; glue plate; dry before printing
PolyMax PC	Engineered PC alloy (partner not disclosed)	113	—	60	Anneal recommended at 100 °C for 2 h to lock in HDT
Polymaker PC-ABS	PC/ABS alloy (explicit)	109	—	40	Vicat 135 °C; entry-level toughness; lowest cost in family
Polymaker PC-PBT	PC/PBT alloy (explicit)	140	—	42	Crystallizing alloy; T_m 223 °C on TDS; chemical resistance step-up
AzureFilm PC-ABS	PC/ABS alloy	—	120	—	Automotive-positioning; budget tier

Table 15.1 — General-purpose consumer PC blends. The T_g spread from 109 °C (Polymaker PC-ABS) to 145 °C (Bambu PC) reflects the alloy-partner choice directly: more ABS lowers T_g, more PC raises it. Procurement note: tensile values from Polymaker products are XY printed-coupon yield, while Prusament and Bambu values are XY tensile strength — not directly comparable as written. Always cross-check the TDS test method before ranking products on tensile.

15.4 PC-CF and PC-GF composites

Fiber-reinforced PC raises stiffness, HDT, and dimensional stability — and lowers warp tendency on long flat parts where unfilled PC's thermal-contraction stress dominates — at the cost of brittleness, abrasion, and substantially compromised Z-strength. Loading is typically 10–30 wt%.

Product	Filler	HDT @ 0.45 MPa (°C)	Tensile yield (MPa)	Notes
Prusament PC Blend CF	~10–15% CF (loading not disclosed)	114	64	Hardened nozzle advised; matches Prusament PC Blend on T_g with stiffness gain
Spectrum PC CF	10% CF	140	76	Vicat 150 °C; dry box yes; hardened nozzle
Ultrafuse PC GF30	30% glass fiber	140	36	T_g 142 °C; very stiff; lower elongation; abrasive; drying 100 °C / 4–16 h
3DXTech CarbonX PC-CF	~15% CF	~140	—	US industrial line; ISO 9001; hardened nozzle mandatory

Table 15.2 — Reinforced PC composites. The Ultrafuse PC GF30 tensile-yield value of 36 MPa is notable: it appears lower than the unfilled PC Blend (~60 MPa) because GF-loaded amorphous polymers fail in brittle mode at the matrix-fiber interface before yielding, so the reported "yield" is effectively a break-strength value. Modulus and HDT are the relevant engineering numbers for these grades, not yield strength. Picking GF30 for tensile applications misreads the data.

15.5 ESD-safe PC

PC in its native form is electrically insulating (surface resistivity ~10^{15} Ω/sq). For electronics housings, IC handling fixtures, ESD-sensitive workspace tooling, and certain aerospace applications, ESD-grade PC is compounded with conductive additives (multi-wall carbon nanotubes or specialty carbon black) to drop the surface resistivity into the electrostatic-dissipative target band of 10^6–10^9 Ω/sq.

Product	Conductive additive	Surface resistivity	HDT @ 0.45 MPa (°C)	Notes
3DXTech 3DXSTAT ESD-Safe PC	Conductive carbon (CNT-class)	10^4–10^9 Ω/sq	135	T_g 143 °C; hardened nozzle mandatory; the consumer-tier ESD-PC default
Prusament PC Space Grade Black	Carbon-based additives (CNT-class)	ESD-dissipative range (TDS-published)	137.6	Specialty tier; published low-outgassing metrics; hardened nozzle required; price premium reflects qualification testing rather than performance step-up

Table 15.3 — ESD-safe PC filaments accessible to consumer users. CNT-loaded filaments are more abrasive than fiber-loaded grades on a per-volume basis because the nanotubes interact with nozzle bore surfaces along their length; PCD or ruby nozzle tips extend service life dramatically on these materials. The Prusament Space Grade price premium (~$269/kg vs ~$50/kg for the standard PC Blend) is a procurement decision rather than a performance one — buy it for the documented outgassing data, not the HDT.

15.6 Flame-retardant PC and PC/ABS-FR

For enclosures near ignition sources, electronics housings subject to UL approval, transit and rail-vehicle applications, and other safety-critical work. FR additives — typically halogen-free phosphorus-based or sulfonate packages — lower flammability ratings to UL94 V-0 (self-extinguishing within 10 seconds of flame removal, no flaming drips). The trade-off matters: FR additives often plasticize the polymer, lowering T_g and HDT by 30–50 °C compared to pure PC.

Product	Class	FR rating	T_g (°C)	HDT @ 0.45 MPa (°C)	Notes
Forward AM Ultrafuse PC/ABS FR Black	PC/ABS + halogen-free FR	UL94 V-0; EN45545-2 R22/R23	94	89	Rail-vehicle certifications make this the procurement default for transit work
Spectrum PC/ABS FR V0	PC/ABS + halogen-free FR	UL94 V-0	—	— (HDT @ 1.8 MPa: 90)	Vicat 104 °C; print 240–265 °C; enclosure recommended for larger parts
Bambu PC FR	PC + FR (halogen content not disclosed)	UL94 V-0 (claim)	145	113	Highest T_g in the FR-PC category; FR additive package not detailed in TDS

Table 15.4 — Flame-retardant PC and PC/ABS filaments. The T_g spread (94 °C for Ultrafuse vs 145 °C for Bambu PC FR) is the key engineering signal: FR compliance and maximum operating temperature are competing goals, and the Bambu product holds its high T_g through the FR compounding more aggressively than the Ultrafuse alloy. Pick by certification first (which standard does your application require?), then by thermal envelope.

15.7 PC/PTFE (low-friction wear surfaces)

PC matrix compounded with PTFE for low-friction sliding surfaces — bushings, guides, wear plates, mechanical interfaces where COF matters. The PTFE phase lowers the coefficient of friction and the wear rate against itself and against metal counterfaces; the PC matrix carries the structural load.

Spectrum PC/PTFE is the most widely available commercial product in this niche, with HDT 140 °C (annealed) and tribological metrics published on the TDS. Print at 265–295 °C nozzle, 90–120 °C bed, with chamber recommended and Magigoo PC adhesive specified by the manufacturer.

Hotend material constraint. PTFE decomposition is a graded process, not a single threshold: fluoropolymer SDS data and NIOSH/PlasticsEurope guidance describe particulate fume release and polymer-fume-fever risk becoming relevant around 300–350 °C, active pyrolysis near 400 °C, and the more hazardous gases — hydrogen fluoride and carbonyl fluoride — appearing at higher temperatures still, roughly 400 °C and above (see §5.3). PC/PTFE filaments process at 280–300 °C nozzle, which is below the onset of PTFE fume release but well above the safe temperature for PTFE-lined hotends (PTFE liners soften and outgas above ~240–250 °C even before decomposition becomes a concern). PC/PTFE printing requires an all-metal hotend without exception; this is the single most common process-incompatibility error on this filament.

15.8 Consolidated property envelope

Across the four product categories above, the property envelope spans a range wide enough that "PC" as a generic spec is operationally meaningless. The table below collects the headline numbers from each category for direct comparison.

Category	T_g range (°C)	HDT @ 0.45 MPa (°C)	Tensile (MPa)	Nozzle (°C)	Best for
General-purpose PC blend	105–150	95–145	40–65	260–290	Default engineering work, electronics enclosures, brackets to 100 °C service
PC-CF / PC-GF composite	142+	140	36–76	275–300	Stiff brackets, fixtures, jigs to 130 °C service; structural parts
ESD-PC	143	135–138	55–70	270–300	Electronics housings, IC handling, ESD-sensitive workspaces, space hardware
FR-PC / PC/ABS-FR	94–145	89–113	50–60	240–280	Safety-critical enclosures, transit/rail-certified parts, UL-rated electronics
PC/PTFE	—	140 (annealed)	55	265–295	Low-friction bushings, guides, wear surfaces; all-metal hotend required

Table 15.5 — PC family consolidated envelope. The T_g range column captures the single most consequential procurement variable across the category: a 50 °C swing on T_g reshapes the service-temperature envelope completely. Specifying "PC" without specifying which sub-category is the most common procurement error in this polymer family — easy to make on a parts BOM, hard to recover from in a production setting.

15.9 Print process and calibration

PC family parameters vary more by sub-category than within any single one. The starting points below assume a 0.4 mm hardened-steel nozzle (PC Blend tolerates brass; everything fiber- or CNT-loaded does not) and an enclosed build space.

Parameter	PC Blend	PC-CF / PC-GF	ESD-PC	FR-PC	PC/PTFE
Nozzle (°C)	270–290	275–300	270–300	240–280	265–295
Bed (°C)	100–115	100–115	110–120	90–110	90–120
Chamber	passive 40–50 °C	passive 40–50 °C	passive 45–60 °C	passive 40–50 °C	active 45–55 °C
Part cooling (%)	0–10	0	0	0–10	0
Max volumetric (mm^3/s)	8–12	6–10	7–10	8–11	6–9
Pressure advance	0.025–0.05	0.035–0.06	0.030–0.05	0.030–0.05	0.030–0.05
Nozzle hardness	brass OK	hardened mandatory; PCD/ruby preferred	hardened mandatory; PCD/ruby preferred	brass OK; hardened on FR-CF variants	hardened recommended
Drying	80–100 °C, 6–8 h	90–110 °C, 8–10 h	80–100 °C, 6–8 h	60–80 °C, 4–16 h	80–100 °C, 6–8 h
Hotend type	any	any	any	any	all-metal only

Table 15.6 — PC family starting print parameters. The hotend-type row is the most overlooked spec: PTFE-lined Bowden-style hotends rated to 240 °C are ubiquitous on Tier 1 hardware and will outgas or degrade at PC processing temperatures regardless of nozzle wear, before any process tuning has a chance to matter. Per-spool calibration on the actual machine remains mandatory; the values above are polymer-chemistry starting points.

Moisture is the second-most-impactful variable. PC absorbs 0.3–0.5% water at saturation; PC-CF and PC-GF substantially more because fiber surface area accelerates uptake. Moisture symptoms: stringing despite tuned retraction, surface roughness, audible "sizzle" or popping in the melt zone, and compromised interlayer bonding. Active drying before every serious print is the standard for engineering work; the Part I §3.5 drying table specifies PC at 80–100 °C for 6–8 h and the reinforced grades at 90–110 °C for 8–10 h. Dry-box storage during printing extends the printable window for opened spools.

15.10 Bed adhesion strategy

PC presents the opposite problem from polypropylene: PC adheres too strongly to smooth PEI when properly hot. The grip is sufficient to tear the spring steel sheet or pull PEI fragments away from the magnetic substrate during part removal. Strategy depends on print volume and how often the surface switches between PC and other materials.

Surface	PC compatibility	Adhesion strategy	Notes
Smooth PEI	Over-grips; sheet damage on removal	Glue stick, PVP coating, or Magigoo PC as release layer	Standard prosumer plate; release layer is non-negotiable for engineering parts
Textured PEI	Acceptable; reduced grip	Bare for small parts; Magigoo PC for larger	Less likely to damage on removal; cosmetic surface texture transfers to first layer

Surface	PC compatibility	Adhesion strategy	Notes
G10 garolite	Best long-term solution	Bare; bed 100–115 °C; cool fully before removal	Engineering default for repeated PC printing; zero adhesive residue; durable across many prints
CryoGrip Glacier	Documented compatibility at moderate bed temps	Bare; bed 90–100 °C	Frost-effect engineered sheet; cold-release on cool-down; lower bed temperatures than PEI
Glass / borosilicate	Marginal	Magigoo PC mandatory	Works but releases unpredictably; not the engineering choice
Polycarbonate sheet	Over-grips catastrophically	Do not use	PC-on-PC bonding is mechanically inseparable on cool-down

Table 15.7 — Bed adhesion strategies for PC family materials. G10 garolite is the engineering default for production PC work because its surface chemistry grips PC during printing and releases cleanly on cool-down without consumable adhesives — a workflow advantage that compounds over many prints.

The cost case for garolite is concrete. Standard spring-steel PEI plates damaged by over-grip during PC removal cannot be repaired; replacement runs $30–60 per sheet and is the dominant ongoing cost of running PC on PEI without a release layer.

15.11 Annealing

PC is amorphous; annealing does not change crystallinity (there is none). What annealing does for PC is relieve residual stress from rapid layer cooling — useful for parts with thick walls, sharp corners, or geometric stress concentrators where as-printed residual stress would otherwise cause delayed cracking. The dimensional cost is modest: typical PC parts shrink 0.3–0.5% during a stress-relief anneal.

Common vendor schedules: PolyMax PC 100 °C for 2 h; Bambu PC and PC FR 85–100 °C for 6–12 h. The temperature must stay below T_g by ~10–15 °C to avoid distortion in thin walls — 100 °C is the practical upper bound for most consumer PC blends despite the T_g being 110–145 °C. Cool slowly (switch oven off, leave the part inside until ambient) to avoid trapping new stress. The PC/PBT alloy (Polymaker PC-PBT) is the exception: the PBT phase is semi-crystalline and responds to annealing similarly to other semi-crystalline polymers, with HDT and stiffness gains beyond simple stress relief. Schedule per the vendor TDS for that product specifically.

15.12 Brand landscape (consumer-accessible)

The consumer-accessible PC market clusters around eight vendors with well-documented engineering-grade SKUs. Sealed-cartridge industrial PC materials (Stratasys PC-ABS and PC-ESD, locked to Fortus/F-series printers) are out of scope per the Part I §1.2 prosumer-tier framing.

Brand	Catalog	Distinguishing notes
Prusament (Prusa Polymers)	PC Blend; PC Blend Carbon Fiber; PC Space Grade Black	Three-tier line from consumer engineering through space-qualified specialty; published printed-specimen data; the most-documented consumer PC brand

Brand	Catalog	Distinguishing notes
Bambu Lab	PC; PC FR	Tuned for reduced shrinkage; specifies chamber 45–60 °C; FR variant carries UL94 V-0 claim; mainstream consumer pricing
Polymaker	PolyMax PC; PolyLite PC; PC-ABS; PC-PBT	Engineered alloys with partner polymers named on the TDS for PC-ABS and PC-PBT; PolyMax PC is the unnamed alloy in the consumer tier
Forward AM (BASF)	Ultrafuse PC/ABS FR Black; Ultrafuse PC GF30	Rail-vehicle FR certification (EN45545-2) on the FR product; GF30 is the stiffest commonly-available PC composite at the consumer tier
3DXTech	3DXSTAT ESD-Safe PC; CarbonX PC-CF; ECO-PC FR (limited)	US industrial line; ISO 9001 manufacturing; ESD product is the consumer-tier ESD-PC default; price 1.5–2× consumer equivalents
Spectrum Filaments	PC CF; PC/PTFE; PC/ABS FR V0	European industrial line; the only consumer-accessible PC/PTFE product; halogen-free FR formulation
AzureFilm	PC-ABS	Budget tier; automotive positioning; published HDT 120 °C
Nanovia	PC family (PC-CF and PC-ABS variants)	French specialty manufacturer; product documentation requires distributor access; mechanical envelope places products in the engineering tier

Table 15.8 — Consumer-accessible PC brand landscape (early 2026). Prusament, Bambu, and Polymaker dominate consumer-tier shelves and account for the majority of community-shared print profiles. Forward AM Ultrafuse and 3DXTech are the engineering-qualification defaults. Spectrum's PC/PTFE is the only consumer access point for that specific composite chemistry. Brand cross-substitution within a sub-category (e.g., Prusament PC Blend vs Bambu PC) is not free — the alloy partner differs even when neither brand names it, and the printed envelope can shift 10–20% on tensile and substantially more on T_g.

15.13 Application fit

Choose general-purpose PC blend when: the part loads mechanically at service temperatures 80–120 °C (engine-bay components away from direct heat, electronics housings in warm environments, machine guards near motors); notched-impact toughness is required (PETG and PCTG cannot match unfilled PC blend on this axis); the part will be solvent-bonded or vapor-finished (PC responds well to dichloromethane bonding for engineering joints, with the handling caveats of §5.3); cost and printability outweigh the maximum thermal envelope.

Choose PC-CF or PC-GF when: the part needs the stiffness of a metal-replacement filament without crossing into PPA territory on cost or process discipline; HDT to 140 °C is required; dimensional stability under load matters more than impact toughness; the design uses fiber-aligned geometry where Z-strength is not the binding constraint. PA6-CF (Chapter 13) is the alternative if moisture is well-controlled and higher impact toughness is needed; PPA-CF (Chapter 14) is the alternative if moisture is uncontrolled or service temperature exceeds PC's ceiling.

Choose ESD-PC when: the application requires surface resistivity in the 10^6–10^9 Ω/sq range with PC-class structural performance — electronics handling fixtures, IC-test jigs, semiconductor tooling. The Prusament Space Grade product additionally addresses vacuum-service outgassing for space-hardware work.

Choose FR-PC when: certification (UL94 V-0, EN45545 for rail, equivalent for aerospace) is in scope. Pick by certification standard first; the thermal envelope follows.

Avoid the PC family when: the part loads outdoors for long durations (BPA-PC yellows under UV; ASA is the right answer); food contact is in scope (BPA migration concerns; PCTG on Tritan resin is the validated alternative); service temperature stays below 80 °C and impact toughness is not the binding constraint (PCTG saves 30–40% on filament cost and prints more reliably); the part requires fatigue resistance under cyclic load (PC notch-cracks; PA612 and PA11 from Chapter 13 retain ductility better).

Part VIII

Specialty and high-performance

Elastomers, niche engineering thermoplastics, sulfones and imides, the PAEK family, support filaments, and biodegradable specialty resins. The polymers in this Part span the widest hardware envelope in the volume — from Tier 1 TPU on any heated bed to Tier 4 PEEK that exceeds the 350 °C / 120 °C / 65 °C prosumer envelope this reference covers. Where a polymer is fundamentally out of reach for consumer hardware, the chapter says so explicitly rather than pretending otherwise.

16. TPU, TPEE, PEBA, and foaming elastomers

Thermoplastic elastomers are the flexible-filament category in commercial FDM — polymers that combine rubber-like elasticity (200–700% elongation at break) with the meltability and recyclability of thermoplastics. **TPU** (thermoplastic polyurethane) dominates the consumer market on volume. **TPE** (thermoplastic elastomer) is an umbrella term covering TPU and several other block-copolymer elastomer chemistries. **TPEE** (thermoplastic polyester elastomer, sometimes COPE) is a polyester-based elastomer with higher heat and chemical resistance than TPU. **PEBA** (polyether block amide, marketed under the Arkema Pebax trade name) is a polyamide-based elastomer with the lowest density and best dynamic-flex performance in the family. **Foaming elastomers** (chemical-blowing-agent flexible filaments) are a separate functional category that reduces printed-part density by 30–50% and is covered in §16.7.

16.1 Chemistry: hard segments and soft segments

Every commercial flexible filament is a block copolymer of alternating hard and soft segments. The hard segments provide mechanical strength, dimensional stability, and the upper service temperature; the soft segments provide elasticity. The chemistry of the hard segment is what distinguishes the four polymer families covered here.

TPU uses aromatic diisocyanate-extended urea or urethane linkages as hard segments, and polyester or polyether polyols as soft segments. Polyester-based TPU has better mechanical envelope, abrasion resistance, and oil resistance; polyether-based TPU has better hydrolytic stability and low-temperature flexibility. Filament TDSs rarely disclose which soft-segment chemistry is in the product.

TPEE (also called COPE — copolyester elastomer) uses semi-crystalline polyester hard segments and amorphous polyether soft segments. The crystalline hard segments produce higher heat resistance (continuous service to ~120 °C vs TPU's ~80 °C) and better creep resistance under sustained load, at the cost of narrower processing windows and more aggressive crystallization shrinkage. TPEE is the elastomer for parts that load mechanically while flexing at elevated temperature; TPU is the elastomer for everything else in that envelope.

PEBA combines polyamide hard segments (typically PA12, sometimes PA11 in the bio-sourced Pebax Rnew grades) with polyether soft segments (typically PTMG or PEG). The polyamide hard segments give PEBA exceptional dynamic-flex performance — among the lowest hysteresis loss per cycle of any commercial elastomer, which is why supercritical-foamed PEBA (Nike's ZoomX, introduced 2017) has dominated top-tier carbon-plate racing midsoles. It is not the universal midsole material, however: expanded TPU (Adidas Boost) remains in wide use, and recent premium foams also draw on supercritical EVA and aliphatic TPU. PEBA's bulk density runs around 1.01–1.04 g/cm^3 (near water density — the lowest of any commercial elastomer), giving it the highest stiffness-to-weight and toughness-to-weight envelopes in the elastomer family. The polyamide hard segments also extend the useful temperature range: PEBA stays flexible down to -40 °C and retains useful stiffness through 100–120 °C continuous service in the stiffer grades. The trade is cost — PEBA filament typically prices at 3–5× equivalent TPU.

16.2 Shore hardness: the headline specification

Shore hardness on the A and D scales is the single most important specification on a flexible filament. The A scale measures soft elastomers (0–100); the D scale measures hard elastomers and rigid plastics (0–100). The scales overlap: Shore 90A is approximately equivalent to Shore 40D. Conventionally, TPU is quoted on the A scale until ~95A, then switches to the D scale at the rigid end; TPEE is quoted across the A and D scales depending on grade; PEBA is quoted almost exclusively on the D scale (Pebax grades run from 25D for the softest commercial product through 72D for the rigid end). Most filament hardness values cluster in well-known bands:

Shore	Typical feel	Print difficulty	Common applications
60A	Soft rubber band; deforms easily under finger pressure	Very difficult; direct drive mandatory; very slow print speeds	Cosmetic grips, soft seals, anatomical models
70A	Soft tire tread; flexes substantially in hand	Difficult; direct drive strongly preferred	Vibration dampers, soft-touch overmolds, soft phone cases
80A–85A / 25D–35D	Medium rubber; comparable to a soft eraser	Moderate; direct drive preferred but Bowden possible	Flexible hinges, gaskets, watch bands, casters; soft PEBA running-shoe applications
90A–95A / 40D–45D	Firm rubber; harder than a typical eraser	Easier; Bowden setups print this range successfully	Drone tires, mechanical bumpers, durable phone cases — the consumer default
60D–72D	Hard plastic with slight flex; comparable to flexible PP	Easy; prints like a slightly rubbery rigid material	Living hinges, snap-fits with high cycle count, industrial bushings, rigid PEBA medical tubing

Table 16.1 — Shore hardness landscape for FDM elastomer filaments. The print-difficulty axis tracks hardness inversely: each 10-point drop on the A scale roughly doubles the printability challenge. Most consumer first-time flexible-filament users should start at 95A — softer materials demand hardware and skill that this hardness range does not require.

16.3 Property envelope

Elastomer mechanical properties are dominated by Shore hardness and base polymer chemistry. The values below are representative ranges; individual filaments vary within each band.

Property	TPU 95A	TPU 64D	TPEE (~55D)	PEBA 40D / 55D
Density (g/cm^3)	1.20–1.25	1.15–1.20	1.10–1.20	1.01–1.04
Tensile strength (MPa)	30–45	40–55	25–40	35–55
Elongation @ break (%)	400–600	200–400	300–500	400–700
Tear strength (kN/m)	80–120	100–150	80–130	100–180
Continuous service (°C)	70–80	70–85	100–120	90–120
Useful low-temp flex (°C)	-20	-20	-30	-40
Compression set (%)	25–40	20–35	15–30	15–25

Property	TPU 95A	TPU 64D	TPEE (~55D)	PEBA 40D / 55D
Hydrolytic stability	fair (polyester) / good (polyether)	fair (polyester) / good (polyether)	good	excellent

Table 16.2 — Elastomer property envelope by family. The PEBA column is the high-performance reference point: low density, broad temperature range, exceptional dynamic flex, excellent hydrolytic stability. For applications where weight, dynamic-flex performance, or wet-service durability matter, PEBA outperforms TPU enough to justify the cost premium; for everything else, TPU is the practical default.

16.4 Print process: the filament-buckling problem

Flexible filaments push the limits of FDM hardware in a way that rigid materials do not. The extruder gear advances filament into the hotend; the filament must resist the back-pressure created by melt flow through the nozzle. Rigid filament does this easily — the filament column is stiffer than the back-pressure. Flexible filament does not: above some critical back-pressure (which depends on the Shore hardness, the filament path geometry, the nozzle restriction, and the print speed), the filament buckles inside the filament path between the extruder gear and the hotend entry, producing under-extrusion or a jammed extruder.

The engineering response is to constrain the filament path. Direct-drive extruders mounted on the toolhead — where the filament traverses ~30–50 mm from gear to nozzle melt zone — print 85A and softer reliably. Bowden-tube extruders with ~500–800 mm of PTFE tubing between gear and hotend struggle with anything softer than 95A. Constrained-path extruders — direct-drive designs that physically constrain the filament between rollers or in a rigid channel all the way to the nozzle entry — print 70A and softer. Single-material multi-extruder hardware that shares one nozzle across several filament feeds typically uses Bowden-style routing between buffer and toolhead, which restricts those systems to 95A and harder TPU unless the vendor specifies otherwise.

PEBA prints more forgivingly than TPU at equivalent Shore hardness. The polyamide hard segments give PEBA filament a stiffer un-melted column than TPU at the same Shore reading, which reduces buckling under back-pressure. A PEBA 40D filament (~90A equivalent) prints reliably on Bowden hardware where a TPU 90A filament would buckle. This is operationally significant for multi-extruder systems with longer filament paths.

Print speed compounds the back-pressure constraint. A flexible filament that prints reliably at 20 mm/s may buckle at 40 mm/s under otherwise-identical conditions because the higher volumetric flow demands a higher melt back-pressure. The first calibration step on any new flexible filament is max volumetric flow at the target nozzle temperature — typically 4–6 mm^3/s for softer grades, 6–10 mm^3/s for 95A, up to 12 mm^3/s for the harder 60D–72D grades. Start lower and walk up.

16.5 Bed adhesion: the over-grip problem

TPU, TPEE, and PEBA all adhere strongly to smooth PEI surfaces — strongly enough to damage the spring-steel sheet on removal of large or geometrically complex prints. The same over-grip problem documented for PC and PETG, amplified because elastomer surfaces deform during removal and create additional stress on the sheet. The standard mitigations apply: glue-stick release layer, PVP coating, dedicated build sheets engineered for elastomers, or substantially lower bed temperatures to reduce grip. Textured PEI grips less aggressively and is the practical default for routine TPU work; smooth PEI with a glue-stick release is appropriate for parts that need a glossy first-layer surface. CryoGrip Glacier is also documented as a successful cold-release surface for TPU; bed temperature 40–50 °C with no adhesive is the typical workflow. PEBA adheres less aggressively than TPU to PEI and typically releases cleanly without adhesive aids at 50–60 °C bed temperature — one of several ease-of-use advantages PEBA carries over TPU in production work.

16.6 Drying

TPU is moderately hygroscopic — typical saturation 0.3–0.8%, less than polyamides but more than polyesters. Moisture symptoms are characteristic and immediately recognizable: visible steam bubbles emerging from the nozzle tip during extrusion, audible popping in the melt zone, severe surface roughness on the printed bead, and substantial strength loss in the printed part. The Part I §3.5 drying table specifies TPU/TPE at 50–65 °C for 4–6 h, with the strong caveat that the upper temperature must stay below the Vicat softening point of the specific filament — softer grades (60A, 70A) deform irreversibly above 55 °C and spool layers can fuse together inside a hot dryer. Bed-style filament dryers running at 50 °C are safe for all grades; convection ovens require careful temperature monitoring on the soft-grade filaments.

TPEE has lower moisture sensitivity than TPU but the same surface-quality symptoms when wet. Drying at 65–75 °C for 6–8 h is standard. **PEBA is the most hygroscopic elastomer in this chapter** by virtue of its polyamide hard segments — which carry the same amide-group moisture behavior as the aliphatic nylons of Chapter 13. Saturation absorption runs 1–2% depending on the grade. Drying at 70–80 °C for 6–8 h is the standard before serious prints; dry-box storage during printing is essentially mandatory for opened spools. The higher safe drying temperature relative to TPU reflects PEBA's higher service temperature.

16.7 Foaming elastomers

Foaming filaments use chemical blowing agents — additives that release gas (typically CO_2 or N_2) at elevated nozzle temperatures — to produce extruded beads with internal microvoid structure. The result is a printed part with 30–50% density reduction, softer feel even at equivalent base-polymer hardness, improved acoustic absorption, and reduced thermal conductivity. The foaming PLA category (colorFabb LW-PLA and equivalents) is the volume leader and is covered in Chapter 6. The foaming-elastomer category is smaller but functionally distinct: combining elastomer elasticity with foam compressibility produces a cushioning material with properties no rigid foaming filament can match.

The foaming mechanism is nozzle-temperature-driven. Below an activation threshold (typically 225–240 °C, vendor-specific), the blowing agent is dormant and the filament extrudes at its nominal density. Above the threshold, the agent decomposes and the foaming begins; foam expansion ratio increases with nozzle temperature up to a saturation point. The operational consequence: **print parameters must be calibrated against the foaming response, not just for surface quality**. A filament that extrudes at 1.0 effective flow rate at 220 °C may extrude at 0.5 effective flow rate at 250 °C because the same volume of solid filament has expanded into twice as much bead volume. Vendor-published process windows specify the target foaming temperature; the slicer flow rate (typically encoded as extrusion multiplier in the 0.5–0.7 range, vs the 1.0 baseline) compensates for the expansion.

Foaming-elastomer brand landscape. Siraya Tech is among the most visible suppliers in the consumer-accessible foaming-elastomer niche, with foaming TPU products engineered for footwear midsoles, custom-fit cushioning inserts, vibration-damping mounts, and orthotic applications. The Siraya Tech foaming line spans both rigid (foaming PLA, marketed under names like Mushroom for the PLA base) and elastomer (foaming TPU) base polymers; the elastomer products are the relevant ones for this chapter. Pricing runs 1.5–2× equivalent unfilled TPU. Specialty European and Asian vendors carry foaming-TPU SKUs at industrial-tier pricing for footwear-prototype applications. **Application fit:** foaming elastomers are the right choice when the part will see cyclic compression loading (running-shoe midsoles are the canonical application), when reduced weight at retained softness matters, or when acoustic damping is a design goal. Avoid foaming elastomers when dimensional precision matters (the expansion ratio drifts per-spool and per-batch enough that mating-surface tolerances are challenging) or when sustained static compression is the load mode (foamed elastomers take a compression set faster than the equivalent unfoamed base material).

16.8 Brand landscape

The flexible-filament market segments by Shore hardness, by base polymer chemistry, and by the price/performance tier. Most major filament manufacturers offer at least one TPU product; specialty elastomer brands (NinjaTek, Recreus) compete on the soft end where general-purpose vendors struggle. PEBA filament is available from a smaller set of specialty vendors. Foaming elastomers are essentially a single-supplier consumer market.

Brand	Notable products	Distinguishing notes
NinjaTek	NinjaFlex 85A; Cheetah 95A; Armadillo 75D	US elastomer specialist; the 85A and softer grades are the consumer-tier benchmark; Armadillo bridges into rigid territory
Recreus	FilaFlex 60A; FilaFlex 70A; FilaFlex 82A; FilaFlex 95A	Spanish specialist; the only commercial 60A elastomer with a developed retail channel; constrained-path extruders mandatory at the soft end
Polymaker	PolyFlex TPU95; PolyMax TPU95; PolyFlex TPU90	Mainstream consumer pricing; PolyMax adds impact-modified envelope; broad color availability
Bambu Lab	TPU 95A; TPU for AMS	TPU for AMS is engineered specifically for constrained-path buffer-fed printing; standard 95A TPU is direct-drive only
Siraya Tech	TPU 64D; Pro Flex 85A; foaming TPU line; Mushroom (foaming PLA)	TPU 64D is the impact-modified rigid-elastomer offering for living hinges and snap-fits; the foaming-TPU products are the consumer-tier reference for midsole and cushioning applications
3DXTech	CarbonX PEBA; specialty TPU grades	US industrial line; the most accessible consumer PEBA filament with published TDS data; hardened nozzle not required but recommended for high-volume use
Forward AM (BASF)	Ultrafuse TPU 64D; Ultrafuse TPU 85A; Ultrafuse TPU 95A; Ultrafuse PEBA	BASF Elastollan TPU resin base; documented mechanical envelope; PEBA SKU is the European-mainstream consumer entry point; industrial-tier pricing
eSun, Sunlu, SainSmart	eTPU-95A; TPU 95A; various TPU 95A products	Budget tier; cosmetic and prototyping use; mechanical envelope variable
Specialty TPEE	3DXTech CarbonX TPC; Polymaker PolyFlex TPU95-HF	TPEE products at the consumer tier are sparse; the named products are the most accessible

Table 16.3 — Elastomer brand landscape (early 2026). The Recreus FilaFlex 60A product is essentially the only consumer access to printable Shore 60A elastomer in the FDM market — printing it successfully requires a constrained-path extruder and substantial hardware investment beyond general-purpose printers. NinjaTek and Polymaker dominate the 85A–95A consumer mainstream. 3DXTech CarbonX PEBA and Forward AM Ultrafuse PEBA are the consumer-tier entry points for polyamide-block elastomer; Siraya Tech's foaming-TPU products are the consumer-tier reference for foaming elastomer applications.

16.9 Application fit

Choose TPU when: the part requires flexibility, vibration damping, or rubber-like compression behavior at room temperature; abrasion resistance matters (TPU outperforms most other elastomers); the application sees brief exposure to oils or aliphatic solvents (polyester-based TPU resists these well, polyether-based less so); cost is constrained and the application tolerates the 80 °C continuous-service ceiling.

Choose TPEE when: the elastomer will see continuous service above 80 °C (engine-bay grommets, high-temperature gaskets, oven-adjacent dampers); creep resistance under sustained load matters more than maximum elongation; oil and fuel exposure is in scope (TPEE outperforms TPU on both).

Choose PEBA when: dynamic flex performance is the binding constraint (athletic footwear midsoles, sporting equipment, repeated-cycle mechanical springs); the part will see uncontrolled humidity in service (PEBA's hydrolytic stability substantially exceeds TPU's); low density matters (PEBA has the lowest density of any commercial elastomer); the temperature range extends from below freezing through 100 °C continuous; cost is justified by performance.

Choose a foaming elastomer when: the design goal is cushioning under cyclic compression (footwear midsoles are the canonical case); reduced weight at retained softness matters; acoustic damping is part of the application; dimensional precision is not the binding constraint (per-spool foaming expansion drift makes tight-tolerance mating surfaces challenging).

Avoid elastomer filaments when: the part needs precise dimensional tolerance (elastomers print with looser dimensional control than rigid polymers); multi-material printing with rigid filaments is required and the rigid material's process temperature exceeds the elastomer's Vicat point; the design loads the elastomer in compression with no relief geometry (elastomer compression set is 15–50% and degrades the application over time).

17. PMMA, POM, PVDF

Three engineering thermoplastics that share a hardware tier (Tier 2 to low Tier 3) but address distinct application axes. PMMA is the optical-clarity polymer with limited heat resistance and brittle behavior. POM (acetal, also marketed as Delrin-class) is the low-friction wear engineering polymer with serious processing hazards. PVDF (Kynar-class) is the fluoropolymer for chemical-resistance applications, with hydrogen fluoride release as a hazard above 300 °C. All three have small commercial filament markets relative to the commodity polymers, and procurement is concentrated among a handful of specialty vendors.

17.1 PMMA (acrylic)

Polymethyl methacrylate — acrylic — is the optical-clarity engineering polymer. Amorphous, T_g ~80–110 °C, tensile strength 60–75 MPa, modulus 3.0–3.5 GPa, transparent in clear grades with light transmittance comparable to glass (~90%). The polymer that windows and aquariums are made of when not made of glass. UV-stable for years of outdoor service without degradation — PMMA's open-air durability is substantially better than PC, PETG, or PCTG.

Printability is the binding constraint. PMMA is brittle, thermally sensitive (the part shrinks and stresses develop during the rapid cooling of FDM layers), and cracks readily during cooling on parts with sharp internal angles or thick-to-thin section transitions. Vendor process windows typically specify nozzle 240–270 °C, bed 100–110 °C, an enclosed chamber (40–55 °C ambient minimum), and explicitly slow first-layer printing to minimize residual stress. Part cooling is set to zero or near-zero — fan cooling exacerbates thermal stress on PMMA and is the most common failure mode for first-time printing of the material.

Brand landscape. PMMA filaments are sparse. Fillamentum PMMA (Czech European-market specialist) is one of the most accessible products with a published TDS reporting tensile 70 MPa, modulus 3.3 GPa, T_g 80 °C, HDT 94 °C. Spectrum offers a PMMA product on a similar TDS envelope. 3D-Fuel and a handful of regional European vendors carry PMMA SKUs. The polymer is rare enough in commercial FDM that it does not have a community-converged calibration baseline; per-spool testing on the actual machine is the norm.

Application fit. Choose PMMA when optical clarity matters, the part will see outdoor UV exposure, and impact loading is not in scope (acrylic is brittle and shatters rather than deforming). Avoid PMMA when impact toughness matters (PETG, PCTG, or PC blend are better choices), when service exceeds 70 °C continuous (T_g ceiling), or when the print geometry has sharp internal angles where thermal stress will concentrate.

17.2 POM (acetal / Delrin-class)

Polyoxymethylene — acetal, sometimes marketed as Delrin-class after DuPont's Delrin trade name — is the engineering thermoplastic for low-friction wear applications. Semi-crystalline, T_m ~165–180 °C, T_g ~-60 °C (well below room temperature, which is why POM is stiff at room temp but tough across the operating range), tensile strength 65–75 MPa, modulus 2.5–3.0 GPa, low coefficient of friction against itself and against most metals, excellent fatigue resistance under cyclic load. The engineering choice for printed gears, cams, sliding mechanisms, low-friction bushings, valves, and any moving mechanical part where wear is the failure mode.

Two serious printing problems. The first is bed adhesion. POM has low surface energy — similar to polypropylene — and does not stick to PEI, glass, or powder-coated steel by chemical means. The community-tested approaches are dedicated POM-coated build sheets (limited commercial availability), glue-stick on glass with elevated bed temperature, or Magigoo PA (which works moderately for POM despite being formulated for polyamide). Warping is severe on parts over ~60 mm; brim is mandatory.

The second problem is a real safety hazard. **POM can release formaldehyde at elevated processing temperatures.** Multiple SDSs warn of heavy formaldehyde fuming above 230 °C, with the rate increasing dramatically near the polymer's decomposition point. Print POM with active ventilation without exception — vented enclosures connected to outdoor exhaust are the engineering standard. The vented-enclosure recommendation also reduces the ultrafine-particle exposure documented for POM, which is higher than most other engineering thermoplastics on a per-unit-print-time basis. POM is the polymer in this volume where the printing-emission section of Chapter 5 is most operationally relevant; review §5.3 before running POM in occupied space.

Brand landscape. Gizmo Dorks Acetal, 3D-Fuel POM, and a few regional specialty vendors offer POM filament. Polymaker has tested POM but does not currently ship a production product. The mechanical envelope is consistent across brands; the printability is consistent across brands too (challenging on every platform tested).

Application fit. Choose POM when wear, low friction, fatigue resistance, or dimensional stability under cyclic load are the binding constraints; the printed surface acts as a moving interface; or the part loads at temperatures where polyamides would absorb moisture and lose stiffness. Avoid POM when bonding to other parts is required (POM does not adhesive-bond reliably; mechanical fastening is the only consistent approach); when active ventilation is not available; when the part is small and cosmetic and cheaper materials would serve.

17.3 PVDF (Kynar-class)

Polyvinylidene fluoride — PVDF, marketed under the Arkema Kynar trade name as the most-recognized commercial grade — is a fluoropolymer with chemical resistance approaching PTFE and substantially better mechanical properties than PTFE in FDM-printable form. Semi-crystalline, T_m 165–175 °C, T_g ~-35 °C, tensile strength 35–50 MPa, modulus 1.5–2.5 GPa, density 1.75–1.80 g/cm^3 (the highest density of any filament in this volume). UV-stable, weatherable, resistant to most acids and acid mixtures, halogens, halogenated solvents, hydrocarbons, and oxidants — but only to weak bases: PVDF is generally serviceable up to roughly pH 12 (homopolymer) or pH 13.5 (Kynar Flex copolymer), and strong caustic above that attacks it. Used in chemical-process equipment, pump components, electronics housings in corrosive environments, and high-purity applications.

Hydrogen fluoride evolution is the principal thermal hazard. PVDF begins to release HF as it degrades — Arkema's Kynar data places the onset around 315 °C, with generation rising sharply by roughly 370 °C rather than switching on at a single point. PVDF processes at 230–250 °C in normal printing, leaving a working margin below that onset, but overheated nozzles, runaway thermal events, and stuck thermistors can drive temperatures into the degradation range. The operational practice is to use a hotend with reliable thermal monitoring and runaway protection, an all-metal hotend without PTFE liners (PTFE itself degrades in a comparable range), and active ventilation. PTFE tubing in the cold-end filament path is acceptable; PTFE-lined hotends are not. Treat the polymer's own SDS as the authority on its specific degradation onset and recommended processing ceiling.

Print process. Nozzle 230–250 °C, bed 90–110 °C, brass nozzle acceptable for unfilled PVDF (no fiber loading), enclosed chamber recommended primarily for warp control rather than chamber temperature. PVDF has good bed adhesion to smooth PEI (no over-grip problem; releases cleanly on cool-down). Drying is generally not required for routine applications — moisture absorption is low (<0.05%) — but engineering-tier applications dry at 80 °C for 4–6 h before serious prints as a baseline discipline.

Brand landscape. 3DXTech FluorX PVDF is one of the most widely available consumer-tier products, with a published TDS and a developed support channel. Specialty European vendors carry PVDF SKUs at industrial-tier pricing. PVDF filament costs run $100–200/kg — the price reflects both the polymer cost and the small market size. **Application fit:** Choose PVDF when chemical resistance to acids, bases, or hydrocarbons is the binding constraint — most acids, halogenated solvents, and hydrocarbons, plus weak bases within PVDF's pH ceiling — and ABS or PETG are not adequate; UV stability over years of outdoor service is required; the application is electronics in a corrosive environment. Avoid PVDF for general-purpose engineering work where PC blend, PA6-CF, or PETG would serve at one-fifth the cost.

18. PPS, PSU, PPSU, PEI

Four high-temperature engineering polymers that share a hardware tier — Tier 3/Tier 4 boundary hardware (nozzle 300–350 °C, bed 110–150 °C, active chamber ≥65 °C) is mandatory for any of them. The bed and nozzle demands here reach past the §4 Tier 3 envelope (bed ≤120 °C), so a fully Tier 3 machine is the practical minimum only for the lower-temperature grades; full Tier 4 (nozzle 380–420 °C, chamber ≥85 °C) is required for unfilled PEI and the high-end PSU/PPSU grades. The polymers themselves have nearly nothing else in common: PPS is semi-crystalline with chemical resistance that approaches PEEK at substantially lower processing temperatures; PSU and PPSU are amorphous sulfone polymers with hydrolytic stability and steam-sterilization compatibility; PEI is amorphous with one of the highest glass transitions of any amorphous polymer reaching commercial filament form (217 °C — above PSU, though just under PPSU) and intrinsic flame retardance.

Consumer accessibility note. Open-spool filament for this polymer family is concentrated in CF-reinforced PPS and PEI products. Unfilled PSU and PPSU are essentially absent from the consumer market — the resin is available industrially but no major filament manufacturer ships a consumer SKU as of early 2026. Unfilled PEI (ULTEM 9085, ULTEM 1010) is available primarily through sealed-cartridge industrial ecosystems (out of scope per Part I §1.2). The consumer-accessible products in this chapter are PPS-CF (multiple brands), CF-reinforced PEI (limited), and limited experimental PSU/PPSU offerings.

18.1 PPS (polyphenylene sulfide)

PPS is an aromatic engineering polymer with continuous-service temperature above 200 °C, chemical resistance to virtually every common solvent and acid below 200 °C, intrinsic flame retardance to UL94 V-0 without additives, and low moisture absorption. Semi-crystalline, T_m ~280 °C, T_g ~90 °C, tensile strength 90–110 MPa (filled grades), modulus roughly 5–12 GPa for printed CF-filled grades (the 10%-CF consumer filaments sit near the bottom of that band — Polymaker Fiberon PPS-CF10 reports about 5 GPa from printed specimens — while higher-CF compounds reach into the low teens), HDT @ 1.8 MPa above 130 °C. The polymer for parts that load mechanically at 150–200 °C continuous, see fuels or oils, or require flame retardance without halogenated additives.

The CF-filled grades are essentially the entire consumer market. Unfilled PPS is challenging to print because the rapid cooling between deposited layers below the polymer's crystallization-onset temperature (~120 °C, requiring chamber temperatures at the very top of Tier 3) produces inconsistent crystallinity that compromises mechanical performance. Carbon-fiber reinforcement at 10–20 wt% suppresses the crystallization shrinkage, gives the matte black surface characteristic of CF-filled polymers, and produces a printable engineering filament. Hardened nozzles are mandatory; the abrasion combines CF wear with PPS-specific tooling wear from the aromatic backbone.

Print process. Nozzle 320–350 °C, bed 110–120 °C, active chamber 55–65 °C, hardened steel nozzle (PCD preferred for production), drying 80–110 °C for 6–8 h. Bed adhesion: G10 garolite is the engineering default; Magigoo PA also works. PPS-CF prints reliably on Tier 3 hardware at the upper end of the chamber-temperature range; below 50 °C chamber, interlayer adhesion falls off above ~80 mm Z-height. Annealing at 200 °C for 2–4 h with packed-sand support is recommended for parts that will load at high temperatures; the annealed crystallinity holds the heat envelope.

Brand landscape. Bambu Lab PPS-CF (mid-2024 launch), Polymaker Fiberon PPS-CF10 (10% CF loading documented), Flashforge PPS-CF (LUVOCOM compound), 3DXTech CarbonX PPS+CF, and Raise3D Industrial PPS-CF are among the more widely available consumer-accessible products. Pricing runs $150–280/kg. Polymaker and 3DXTech publish the most detailed TDS data; the Bambu product is the most visible by community adoption. PPS-CF is the right answer when the application loads above 150 °C continuous and PPA-CF (Chapter 14) is not enough.

18.2 PSU (polysulfone) and PPSU (polyphenylsulfone)

Polysulfone (PSU) and polyphenylsulfone (PPSU) are amorphous engineering polymers in the sulfone family — characterized by the sulfone linkage (–SO_2–) in the polymer backbone. Both have very high T_g (PSU ~185 °C, PPSU ~220 °C), exceptional hydrolytic stability (PPSU can survive repeated steam-autoclave cycles indefinitely), and transparent or amber-tinted optical appearance. The polymers behind medical instruments, aircraft cabin parts, and high-temperature plumbing fittings in industrial-scale manufacturing.

Process requirements push above the prosumer envelope. PSU prints at 350–400 °C nozzle, 140–155 °C bed, 65 °C chamber minimum. PPSU prints at 370–410 °C nozzle, 140–155 °C bed, 65 °C chamber. Both numbers cross the upper edge of the Tier 3 envelope this volume defines (350 °C nozzle, 120 °C bed, 65 °C chamber). Consumer hardware that nominally reaches those temperatures often does so unstably; reliable PSU/PPSU printing demands hardware that is also out of scope here. The polymer is in this chapter because it exists in the commercial filament market and consumers ask about it, not because it's a practical choice for prosumer FDM.

Brand landscape. 3DXTech ThermaX PSU and ThermaX PPSU are the consumer-accessible products; pricing $250–500/kg. The realistic procurement path for PSU/PPSU parts is industrial outsourcing or sealed-cartridge industrial printers — both outside this volume's scope. For consumer users encountering an application that calls for PSU or PPSU, the practical alternatives are PPS-CF (for the heat envelope) or PC blend with FR additives (for the autoclave-resistance niche without the heat ceiling).

18.3 PEI (polyetherimide / ULTEM-class)

Polyetherimide is an amorphous high-temperature polymer best known under the SABIC ULTEM trade name — ULTEM 9085 and ULTEM 1010 are the two dominant grades in industrial FDM. Tensile strength 85–105 MPa, modulus 3.0–3.5 GPa, T_g 215–220 °C, HDT @ 1.8 MPa 170–200 °C, intrinsic flame retardance to UL94 V-0, very low smoke emission during combustion (the characteristic that drives PEI's aerospace and rail-vehicle adoption). Amorphous, so no crystallization-related dimensional behavior to manage — printed parts are dimensionally consistent.

Process requirements are firmly Tier 4. PEI prints at 370–420 °C nozzle, 140–155 °C bed, 85 °C minimum chamber. Drying at 130–150 °C for 4–6 h is mandatory — moisture at print temperatures of 400 °C produces catastrophic flashing inside the melt zone. Hardware capable of these temperatures stably exists but is not consumer-tier.

Consumer accessibility. Open-spool PEI filament accessible to hobbyist users is limited to CF-reinforced grades from 3DXTech (ThermaX PEI 9085 CF, ThermaX PEI 1010 CF) and a few specialty vendors. Unfilled PEI 9085 and PEI 1010 are dominated by sealed-cartridge industrial ecosystems (out of scope). For applications that require true PEI performance (UL94 V-0 with high heat envelope, aerospace certifications, low-smoke combustion), the practical procurement path for consumer users is industrial outsourcing rather than in-house printing. PEI is in this volume primarily for context and to set the boundary of what prosumer FDM can and cannot reach.

18.4 Consolidated comparison

Polymer	Crystallinity	T_g (°C)	Continuous service (°C)	Nozzle (°C)	Consumer access
PPS-CF	Semi-crystalline	90	180–200	320–350	Mainstream consumer; multiple brands
PSU	Amorphous	185	150–170	350–400	Specialty only (3DXTech); above prosumer envelope
PPSU	Amorphous	220	180–200	370–410	Specialty only (3DXTech); above prosumer envelope
PEI 9085-CF	Amorphous	186	170	350–390	Specialty (3DXTech); top of Tier 3
PEI 1010-CF	Amorphous	217	200	370–420	Specialty (3DXTech); Tier 4 hardware required
PEI unfilled	Amorphous	217	200	370–420	Sealed-cartridge industrial only — out of scope

Table 18.1 — High-temperature engineering polymer family at a glance. PPS-CF is the only polymer in this group that prints reliably on Tier 3 prosumer hardware; everything else either requires Tier 4 hardware or is locked to industrial-cartridge ecosystems. For consumer users with applications in this thermal envelope, PPS-CF is the practical engineering answer; PEI and the sulfones are aspirational unless industrial hardware or outsourcing is on the procurement path.

19. PAEK family (PEEK, PEKK)

The polyaryletherketone (PAEK) family is the apex of FDM thermoplastics: continuous-service temperatures of 250 °C, mechanical properties that rival cast aluminum at about half the density, chemical resistance approaching PTFE, and — in implant-grade resin formulations — a biocompatibility record behind decades of cleared medical devices. PEEK (polyetheretherketone) is the volume leader; PEKK (polyetherketoneketone) exists in amorphous and semi-crystalline variants with somewhat lower T_m. The polymer family is engineering metal-replacement in aerospace, automotive, oil-and-gas, and medical applications.

This chapter exists to bound the volume's scope rather than enable consumer PAEK printing. PAEK processing requires nozzle 380–440 °C, bed 140–155 °C, active chamber ≥85 °C, drying at 120–130 °C, and post-print annealing for crystallinity. Every line item exceeds the Tier 3 prosumer envelope this volume covers. Consumer-tier FDM hardware labeled as PEEK-capable typically reaches the nozzle temperature briefly and unstably, lacks the active chamber that PEEK crystallinity demands, and produces parts whose mechanical performance is a fraction of the industrial standard. Consumer PAEK printing is possible on small parts with substantial caveats; reliable PAEK printing is not. Hobbyists who need PEEK parts almost universally find industrial outsourcing the practical procurement path.

19.1 PEEK (polyetheretherketone)

Semi-crystalline. T_g 143 °C, T_m 343 °C, tensile strength 90–100 MPa (unfilled), 130–170 MPa (CF-filled), modulus 3.5–4.0 GPa unfilled and up to 12–15 GPa for CF-filled grades, continuous service temperature 240–250 °C. The polymer chemistry has been industrially mature since the 1970s; the FDM-specific compounding (filament-grade resin processing, diameter tolerance, moisture protection) is a more recent development.

Crystallinity is the dominant printed-part variable. Rapid cooling during FDM deposition produces partially amorphous PEEK with mechanical performance well below the resin spec. Active chamber temperatures of 150–200 °C during printing — industrial-tier territory — produce semi-crystalline parts with the full PEEK envelope. Chamber temperatures of 85–110 °C (the consumer Tier 3 upper bound) produce intermediate results that still require post-print annealing (140–200 °C for 2–4 hours) to develop full crystallinity. The annealing step shrinks the part 1–3% and can warp thin walls.

19.2 PEKK (polyetherketoneketone)

PEKK is a PAEK family member differentiated by molecular structure — a different ratio of ether linkages to ketone linkages along the backbone. Commercial PEKK exists in two principal variants: PEKK-A (amorphous, T_g ~165 °C, no T_m, processes amorphously and stays amorphous) and semi-crystalline PEKK (T_g ~165 °C, T_m ~310–340 °C depending on grade, develops crystallinity on cooling and during annealing). Amorphous PEKK processes more easily than PEEK because it does not require active chamber crystallization; semi-crystalline PEKK behaves similarly to PEEK in printing. PEKK is the practical PAEK-family choice for printers that cannot reach PEEK's process temperatures stably.

19.3 Consumer accessibility and brand landscape

Open-spool PAEK filament accessible to hobbyist users clusters around a small set of specialty vendors:

Brand	Products	Notes
3DXTech	ThermaX PEEK; ThermaX PEEK-CF; ThermaX PEKK-A; ThermaX PEKK-CF	The US specialty leader for consumer-accessible PAEK; ISO 9001; comprehensive published TDS; pricing $300–500/kg
Polymaker	PolyMide PA12-CF Pro (positioned as PEEK alternative)	Polymaker does not currently ship a true PAEK product; targets the application space with reinforced polyamide
Flashforge / specialty Asian	PEEK / PEEK-CF (limited)	Available but TDS documentation thin; pricing competitive but mechanical envelope variable
Generic Chinese specialty	PEEK / PEEK-CF	Budget tier with substantial quality variance; mechanical envelope below specialty leaders; appropriate for prototyping only

Table 19.1 — Consumer-accessible PAEK filaments. The realistic procurement path for hobbyist PAEK applications is 3DXTech ThermaX PEEK-CF or PEKK-CF on hardware that meets the Tier 4 envelope. Sealed-cartridge industrial PAEK ecosystems (Stratasys F900 with PEKK, industrial Roboze with PEEK) are out of scope. Treat consumer PAEK as a niche specialty filament accessible only to users who have invested in the supporting hardware tier.

19.4 Application fit

Choose PEEK when: the application requires continuous service above 200 °C with full mechanical performance; the part will be made from an implant- or medical-grade PEEK resin through a qualified, validated process where biocompatibility is a requirement; chemical resistance and thermal endurance together exceed what PPS-CF can deliver; and the supporting hardware tier is available. **Choose PEKK when:** the application tolerates PEKK's slightly lower thermal envelope (typical 220–240 °C continuous vs PEEK's 250 °C); amorphous PEKK-A is acceptable because post-print crystallization is operationally difficult; cost reduction over PEEK is meaningful.

A caution on medical and implant claims. PEEK's biocompatibility record belongs to specific implant-grade resin grades used in cleared, validated device workflows — not to PEEK filament generically. The first FDA-cleared 3D-printed PEEK implant was cleared as a complete system: a named implant-grade resin, a specified printer, defined modeling software, and a pre-validated production process, with full lot traceability and post-build testing. Regulatory clearance attaches to that device and process, and is granted device-by-device. A part printed from ordinary PEEK filament on prosumer hardware is not an implant and carries no biocompatibility status; treat any medical-contact use as requiring its own qualification against the relevant standards (e.g. ISO 10993) and regulatory pathway.

For most consumer users: PPS-CF (Chapter 18), PPA-CF (Chapter 14), or PA6-CF (Chapter 13) almost certainly meets the application requirement at a fraction of the cost and process discipline. The PAEK family is the right answer when the application requirement is genuinely above what those polymers can deliver, and that boundary is high: continuous service above 200 °C, autoclave compatibility, certain biocompatibility certifications. Below that boundary, choosing PAEK is over-engineering.

20. Soluble support polymers (PVA, BVOH, proprietary)

Soluble support filaments enable internal geometries and overhangs that breakaway supports cannot reach: enclosed cavities, undercut features, trapped overhangs, and parts where surface finish in the support-contact area must be smooth. The supports are printed alongside the model in dual-extruder or single-extruder multi-material configurations, then dissolved away in a water bath after printing. Two principal chemistries dominate the consumer market — PVA (polyvinyl alcohol) and BVOH (butenediol vinyl alcohol copolymer) — with several proprietary alternatives for specific applications.

20.1 PVA (polyvinyl alcohol)

PVA is the original FDM soluble-support material. Water-soluble at room temperature, hydrophilic by design. The polymer dissolves slowly in cold water (hours for small parts, overnight for larger), faster in warm water (40–60 °C), and very fast with mechanical agitation. Print at 195–220 °C nozzle, 50–65 °C bed, very low part-cooling fan, brass nozzle acceptable. Compatible with PLA primarily (matched temperature window) and with PETG in some configurations.

Hygroscopic by design and aggressive about it. PVA absorbs moisture rapidly from ambient air — a spool stored at 50% relative humidity for a few days can pick up enough moisture to clog the nozzle on first use. The polymer's water-solubility translates directly to its moisture-uptake behavior. Active filament drying (45–60 °C for 8–12 h) before every print is mandatory; printing directly from a heated dry box is the standard production workflow. PVA stored in ambient air for weeks is functionally ruined for printing — the moisture content does not fully reverse with normal drying.

20.2 BVOH (butenediol vinyl alcohol copolymer)

BVOH is a more recent soluble support chemistry — a copolymer of butenediol and vinyl alcohol. The butenediol units improve thermal stability over pure PVA, raise the practical print temperature window to 200–225 °C, and (most importantly) improve compatibility with PETG and ABS where pure PVA fails because of temperature mismatch. BVOH dissolves faster in water than PVA and produces less swelling during dissolution, which is meaningful for delicate internal geometries that PVA's volumetric expansion would damage.

BVOH is the engineering upgrade. Where PVA paired only with PLA reliably, BVOH pairs with PLA, PETG, ABS, and (with careful chamber temperature management) some nylons. Price runs 2–3× pure PVA. For dedicated multi-material work, BVOH is the practical default; PVA remains the cost-conscious choice for PLA-only soluble-support applications.

20.3 Brand landscape

Brand	Product	Class	Notes
Polymaker	PolyDissolve S1	BVOH-class	High-performance soluble support; compatible with PLA, PETG, ABS, ASA, TPU; mainstream consumer pricing
eSun	eSun PVA	PVA	Budget tier; PLA pairing; significant brand-to-brand variance in moisture sensitivity
Verbatim	Primalloy PVA, BVOH	Both	European mainstream; well-documented TDS data; PLA and PETG compatible
FormFutura	Atlas Support	PVA-class	European specialty; multi-material PLA workflow focus
Specialty break-away	PolySupport (Polymaker), Bambu Support W	Mechanical breakaway	Not soluble; mechanical removal; suitable when soluble supports are not available or compatibility is the issue

Table 20.1 — Soluble and breakaway support filament landscape. The Polymaker PolyDissolve S1 product is the consumer-tier default for BVOH-class soluble supports; the eSun PVA is the consumer-tier default for budget PLA-only workflows. Cross-brand soluble-support substitution is not free — the dissolution kinetics, the swelling behavior, and the moisture sensitivity vary substantially even within the same nominal chemistry.

20.4 Multi-material workflow considerations

Soluble supports require dual-extruder, IDEX, or single-nozzle multi-material hardware. Single-nozzle systems that share the melt zone between model and support filaments introduce a purge requirement at every filament transition — typically 50–200 mm^3 of purge per swap. Soluble support workflows can generate purge-tower volumes that exceed the model volume on small parts, which is the principal cost-of-printing argument against soluble supports for casual users. Dual-hotend and IDEX systems do not have this purge tax but introduce mechanical complexity in the toolhead.

Dissolution workflow. Submerge the printed part in warm tap water (40–60 °C) with gentle agitation. Small parts dissolve in 1–4 hours; large parts overnight. Mechanical removal of bulk support material before dissolution accelerates the process significantly — peel away accessible support, then submerge for the trapped interior. Used dissolution water can be disposed of via household drains (PVA and BVOH are not regulated wastes), though prolonged dissolution will load the water with polymer to the point that refresh is needed.

21. Niche biodegradables (PHA, PCL, PVB)

Three polymers that share a positioning — biodegradable or solvent-finishable specialty filaments outside the commodity mainstream — without sharing chemistry, applications, or process windows. PHA (polyhydroxyalkanoate) is a bacterially fermented polyester used as a PLA toughness modifier and as a standalone biodegradable filament. PCL (polycaprolactone) is a low-melting polymer used in medical and orthotic applications because it can be post-formed in warm water. PVB (polyvinyl butyral) is an isopropyl alcohol-smoothable filament for cosmetic prints. None are mainstream; each has a specific application niche where it is the right answer.

21.1 PHA and PLA/PHA blends

Polyhydroxyalkanoate is a family of polyesters produced by bacterial fermentation of plant-derived sugars — the most genuinely biodegradable commodity thermoplastic available. PHA composts in both industrial and marine environments at reasonable rates, where PLA requires industrial composting facilities to break down meaningfully. Pure PHA is brittle and challenging to print as a standalone filament; PLA/PHA blends combine PLA's printability with PHA's biodegradation advantage and improved layer adhesion.

Brand landscape. colorFabb PLA/PHA was the original commercial PLA/PHA blend and remains the consumer-tier benchmark — typical formulation 10–20% PHA in PLA matrix, tensile strength 60+ MPa, elongation a few percent. colorFabb allPHA is the pure-PHA filament — published mechanical envelope, biodegradation timeline, and unusual printing behavior ('cold bed' configuration recommended, high fan cooling for layer adhesion). Fillamentum's NonOilen line is positioned similarly. Print process for PLA/PHA matches standard PLA closely; pure PHA requires per-vendor process tuning. **Application fit:** PLA/PHA is the right choice when the biodegradability story matters and PLA printability is the binding constraint; pure PHA is the right choice for genuinely compostable single-use parts where cost is not the dominant factor.

21.2 PCL (polycaprolactone)

Polycaprolactone is an aliphatic polyester with an unusually low melting point — T_m ~60 °C, low enough that printed parts can be reformed in warm tap water without specialized equipment. This single property drives every PCL application: medical orthotics that need post-printing fit adjustment to the patient, dental thermoforms, custom braces, exoskeletal supports. The polymer prints at very low temperatures (85–95 °C nozzle), bed unheated or barely warm, on standard hardware with minimal process tuning.

The application is constrained. PCL parts cannot be used in any service environment that approaches body temperature (the polymer softens noticeably above 40 °C and loses dimensional stability above 50 °C). The medical-orthotic application is essentially the entire consumer market for PCL filament. **Brand landscape:** 3D4Makers PCL is the most-documented consumer product; specialty medical-grade PCL filaments exist at substantially higher pricing for qualified medical-device applications. **Application fit:** PCL is the right answer for room-temperature parts that must be post-formed in warm water; for nothing else.

21.3 PVB (polyvinyl butyral)

Polyvinyl butyral is best known industrially as the interlayer in laminated safety glass. In FDM filament form it occupies the cosmetic-printing niche via a single distinctive property: PVB is the only commercial FDM filament that smooths with isopropyl alcohol. The IPA-smoothing workflow produces near-glossy surface finishes without the chemical-handling complexity of ABS acetone smoothing — IPA is a household-tier solvent rather than a regulated industrial chemical.

Two structural limitations. First, PVB has low layer-to-layer adhesion compared to PLA or PETG — the same property that enables IPA smoothing (PVB swelling in IPA) also produces weaker interlayer bonds in the unsmoothed print. Second, PVB is highly hygroscopic — drying schedules around 45 °C for 8 h are vendor-specified, and printed-from-ambient-air spools often print poorly. Print at 215 °C nozzle, 75 °C bed, standard prosumer hardware.

Brand landscape. Prusament PVB is among the most widely used consumer products, with a developed support channel and broad color availability. A handful of regional European vendors carry PVB SKUs. **Application fit:** PVB is the right choice for cosmetic prints where the IPA-smoothable finish is the design goal — display models, decorative parts, parts intended for vapor-smoothing aesthetics — and where layer strength is not the binding constraint. Avoid PVB for functional parts (low layer adhesion limits mechanical performance) or for storage-sensitive applications (humidity will degrade unprotected spools fast).

Part IX

Cross-cutting workflows

Material selection, calibration, bed adhesion, multi-material printing, post-processing, cost/procurement, and tribological filaments — seven synthesis chapters that consolidate the per-polymer guidance scattered through Parts II–VIII into single-purpose references. Read these once after the polymer chapters; return to them as workflow questions arise.

22. Material selection decision framework

Polymer selection is the engineering decision that constrains every downstream choice on a print — process parameters, hardware, post-processing, cost, and ultimately service performance. The framework below is sequential: filter by the hardest constraint first, then refine through the softer ones. When two polymers tie on the binding constraint, pick the cheaper or more printable one — the volume's chapters cover when the second-tier choice is the right one to spend on.

22.1 The four decision axes

Service temperature is the first filter. The polymer's glass transition (for amorphous polymers) or melting/crystallization envelope (for semi-crystalline) sets a hard ceiling on continuous-load service: parts loaded above T_g creep, parts loaded near T_m deform. Add a 20–30 °C margin for engineering work. **Mechanical character** is the second filter: stiffness vs toughness vs flexibility. Most FDM polymers are stiff (PLA, PETG, PC, nylons); a minority are tough (PCTG, PC blend, PPA-CF, PEBA); a few are flexible (TPU, TPEE, PEBA). **Environment** is the third filter: UV exposure, chemical contact, moisture, fuels, food contact, biocompatibility. **Cost and printability** are the fourth filter — usually a tie-breaker rather than a primary constraint, but decisive when the application has no special requirement on the other three axes.

22.2 Decision walkthrough

The sequence below answers "which polymer" by elimination. Each step rules out polymers that fail the current constraint; the surviving set is the right answer.

Step	Question	If yes →	If no →
1	Does the part need to be flexible (Shore D < 70)?	TPU, TPEE, PEBA, foaming elastomer (Ch 16)	Continue to step 2
2	Does the part see continuous service above 200 °C?	PPS-CF if available; otherwise PAEK or outsource (Ch 18–19)	Continue to step 3
3	Does the part see continuous service above 100 °C?	PPA-CF, PC blend (high-PC), PPS-CF (Ch 14, 15, 18)	Continue to step 4
4	Outdoor UV exposure over months or years?	ASA, PMMA, PVDF (Ch 10, 17)	Continue to step 5
5	Aggressive chemical exposure (acids, bases, hydrocarbons, fuels)?	PP, PVDF, PPS, POM by chemistry (Ch 11, 17, 18)	Continue to step 6
6	Food or water contact?	PCTG on Tritan resin (preferred), PP, PCTG (Ch 8, 11)	Continue to step 7
7	Repeated impact loading or living-hinge cycling?	PCTG, PA6/PA12, PP unfilled, PEBA (Ch 8, 13, 11, 16)	Continue to step 8
8	High stiffness-to-weight for structural parts?	PA-CF, PPA-CF, PC-CF, PPS-CF, PEBA (Ch 13, 14, 15, 18, 16)	Continue to step 9
9	Wear, friction, or sliding-contact applications?	POM, PC/PTFE, iglidur PA6 (Ch 17, 15, 13)	Continue to step 10
10	ESD-dissipative surface required?	ESD-PC (Ch 15)	Continue to step 11
11	Flame retardance (UL94 V-0) required?	FR-PC, PPS, PEI (Ch 15, 18)	Continue to step 12

Step	Question	If yes →	If no →
12	Optical clarity required?	PCTG (Ch 8), PETG clear, PMMA, PC clear (Ch 7, 17, 15)	Continue to step 13
13	None of the above special requirements apply?	PETG (cost), PLA (printability), PCTG (toughness step-up)	—

Table 22.1 — Sequential material selection decision walkthrough. Each yes answer terminates the walk and selects from the listed polymers; each no answer continues to the next step. The order of the steps reflects the frequency at which each constraint is binding in practical FDM applications — flexibility and high-temperature service are the most decisive filters; default-tier polymer choice (step 13) handles the bulk of all hobbyist work.

22.3 Quick-reference: by application

Application class	Default polymer	Step-up if budget allows
Display models, cosmetic prints	PLA	PCTG for toughness, PETG for cost
Functional prototyping (room-temp)	PETG	PCTG for impact, PC blend for heat
Outdoor parts (UV, weather)	ASA	PMMA for clarity, PVDF for chemistry
Electronics enclosures (passive)	ASA or PETG	PC blend for heat tolerance
Engine-bay / under-hood	PC blend	PPA-CF for stiffness + heat
Drone or RC airframe	PCTG or PP-CF	PA6-CF or PPA-CF for performance
Lab equipment, chemical contact	PP	PVDF for aggressive chemistry
Living hinges, snap-fits (high cycle)	PP unfilled, PA12	PEBA for dynamic flex
Gaskets, vibration dampers	TPU 95A	TPEE for heat, PEBA for dynamic flex
Wear surfaces, low-friction bushings	POM	PC/PTFE for chemistry, PEEK for heat
Structural brackets, fixtures	PETG or PC blend	PA6-CF or PPA-CF for stiffness
Food contact (resin-level compliance)	PCTG on Tritan	Verify per-filament certification
Athletic footwear, cushioning	PEBA or foaming TPU	—
Aerospace, FR-rated electronics	FR-PC	PEI if hardware tier supports it

Table 22.2 — Application-to-polymer quick reference. Use as a starting point for procurement decisions; the per-polymer chapters in Parts II–VIII carry the engineering detail needed to confirm fit and the brand surveys needed for purchasing.

23. Calibration workflow (unified)

Every new filament — even a re-order of a previously calibrated brand and color — requires per-spool calibration on the actual machine before engineering-grade work. Resin batches drift, additive packages change between revisions, and printer state shifts with nozzle wear, extruder gear wear, and ambient conditions. The workflow below is the consolidated sequence the rest of this volume references; the sequence is order-sensitive — each step's output is the input to the next.

A word on scope before the workflow. Full calibration is worth the time when the print is functional — a part that bears load, mates with other parts to a tolerance, seals, runs hot, or will be tested or certified. For those prints the dimensional accuracy, mechanical strength, and repeatability the workflow buys are the whole point. For purely decorative or cosmetic prints — display models, figurines, visual prototypes — most of this sequence is overkill. A model that only has to look right does not need a measured extrusion multiplier or a tuned pressure-advance value; the vendor's generic profile, perhaps with a quick temperature check for surface finish, is sufficient, and the hours spent on flow and shrinkage calibration return nothing visible. The judgment is simply whether the print has a job to do beyond being looked at. The rest of this chapter assumes the answer is yes; if it is not, drying (Step 1) and a temperature check (Step 2) are the only steps that meaningfully affect a cosmetic result, and the remainder can be skipped without consequence.

23.1 Step 1 — Dry the filament

Drying is the first step because moisture confounds every measurement that follows. A wet filament shows artificially low max volumetric flow (steam disrupts melt cohesion), artificially low effective extrusion multiplier (voids in the bead reduce mass per unit length), and wildly inconsistent pressure advance values. The Part I §3.5 drying-protocol table is the reference; dry to the upper end of the recommended range and time, with 30 minutes margin beyond the spec to be safe on first calibration.

23.2 Step 2 — Temperature tower

A temperature tower prints a single tall geometry with the nozzle temperature stepped down by 5 °C per 30 mm band, spanning the vendor's recommended range plus 5 °C above and below. Score each band on three axes: surface finish (smooth and consistent), bridging (no sag), and stringing (no fine filaments between features). The optimal temperature is the lowest band that scores well on all three — lower temperatures tighten the process window and reduce thermal stress in the printed part. Stock temperature-tower model files exist on community model repositories; the specific tower geometry is less important than scoring the bands consistently.

23.3 Step 3 — Max volumetric flow

Max volumetric flow (mm^3/s) is the rate at which the hotend can melt and extrude filament without under-extrusion. The test prints a single-wall geometry with the flow rate stepped upward — typical bands span 5 mm^3/s to 20 mm^3/s in 1 mm^3/s steps. The failure point is visible as a sudden transition from solid wall to thin, gappy, or visibly under-extruded bead. The max volumetric flow is the highest band before that failure, less a 20% safety margin. Engineering-grade work uses 60–70% of the max value to build process margin against drift; production-tier work runs at the lower end of the band.

23.4 Step 4 — Extrusion multiplier (12-sample wall measurement)

Extrusion multiplier (EM, also called flow or flow ratio depending on the slicer) is the scaling factor applied to the slicer's calculated extrusion volume. The default value of 1.0 assumes perfect filament diameter, perfect extrusion stepper calibration, and zero melt-shrinkage during cooling — rarely all true simultaneously. The 12-sample wall measurement method: print a single-wall hollow cube at a known wall-width slicer setting (typical 0.45 mm for a 0.4 mm nozzle). After cooling, measure the actual wall thickness with calipers at 12 points distributed around the cube. Compute the average; divide the slicer's target wall width by the measured average to get the EM correction. Apply, re-print, re-measure to verify within ±0.5%. Typical converged EM values: 0.93 for high-fiber-loaded grades, 0.97–1.00 for unfilled engineering polymers, 1.03–1.05 for softer elastomers and PC blends.

The YOLO method — a faster alternative for many users. The wall-measurement method has one real weakness: a caliper reading on a single ~0.45 mm wall is at the edge of what hand calipers resolve reliably, and the vase-mode print itself can vary in width with cooling and seam placement. The YOLO flow-rate test, built into OrcaSlicer (and available as community test models for other slicers), sidesteps the caliper entirely. It prints a single plate of small blocks, each sliced at a slightly different flow modifier — typically a range of –0.05 to +0.05 in steps of 0.01 — and the user picks the block with the cleanest top surface: the smoothest fill, no gaps between the surface-pattern arcs, and no raised or sunken seam between the inner and outer regions. The chosen modifier is applied as `new = old ± modifier` in a single pass. Because surface quality is judged rather than measured, YOLO is often the better choice for unfilled polymers on a well-behaved machine: it is faster, needs no calipers, and judging "is this surface smooth" is a more forgiving task than resolving hundredths of a millimetre on a thin wall. The wall-measurement method still earns its place where an *absolute, traceable* number is wanted — qualifying a new material, documenting a profile for publication, or calibrating fiber-filled and elastomeric grades whose top surfaces are textured enough that the visual judgment becomes ambiguous. A reasonable default: YOLO for routine per-spool tuning, the 12-sample measurement when the value has to be defensible.

23.5 Step 5 — Pressure advance

Pressure advance (PA, sometimes Linear Advance) compensates for the elastic lag between extruder gear motion and nozzle bead deposition. Without PA, the bead width drifts at the start and end of every line — thin entries, thick exits. The test prints a single-layer pattern with the PA value stepped upward across the bed; the optimal value is the band where line ends and beginnings appear visually consistent with the rest of the line. Typical converged PA values: 0.020–0.040 for PLA, 0.030–0.060 for PETG/PCTG, 0.025–0.050 for PC blends, 0.04–0.08 for fiber-reinforced polymers.

23.6 Step 6 — XY shrinkage compensation

Amorphous polymers shrink 0.3–0.5% in the print plane on cooling; semi-crystalline polymers can shrink 1.5–3% depending on crystallization behavior. The XY compensation factor in the slicer scales the model outward to compensate, producing dimensionally accurate parts on cool-down. The Califlower Mk2 model — a multi-feature shrinkage test with both external and internal dimensional checks — is the practical community-standard reference. Print, measure key dimensions, compute the average shrinkage as a percentage, set the slicer compensation. Typical converged values: 0.20% for PCTG, 0.25% for nylons, 0.35% for ABS, 0.45% for ASA, 0.5% for unfilled PP.

23.7 Step 7 — Z shrinkage

Z-direction shrinkage is typically smaller than XY because the layer-by-layer deposition allows partial relaxation between layers. The standard test is a 100 mm tall hollow cylinder; measure the actual height with calipers, compute the shrinkage percentage, set the slicer compensation. Many users skip this step on first calibration — the magnitude is usually under 0.3% for amorphous polymers, where engineering tolerance permits it. Skip with intention rather than by accident.

23.8 Storing the calibrated profile

Calibrated values belong in the filament profile, not in the printer's persistent storage. Most slicers support per-filament storage of nozzle temperature, bed temperature, max volumetric flow, EM, PA, XY shrinkage, and chamber temperature. The pressure advance value can also be embedded in the filament-specific start G-code if the firmware supports it (the command differs by firmware: `M900 K[value]` on Marlin, `M572 D0 S[value]` on RepRapFirmware and Prusa Buddy firmware, and `SET_PRESSURE_ADVANCE ADVANCE=[value]` on Klipper). Store the profile, label it with the calibration date and the spool batch code, and re-verify EM and PA on first use of a new spool from the same brand — batch-to-batch drift of 5–10% is normal.

24. Bed adhesion strategy by polymer family

Bed adhesion is the interfacial chemistry problem framed in §3.3: wetting and intermolecular attraction between the molten first-layer polymer and the build surface. Polar polymers grip polar surfaces (PEI, glass, powder-coated steel); non-polar polymers (PP, PE) require non-polar compatible surfaces. The per-family chapters in Parts II–VIII cover the specifics; this chapter consolidates the choices into one table.

24.1 Consolidated bed-adhesion reference

Polymer family	Best surface	Adhesive/release	Bed (°C)	Removal notes
PLA	smooth PEI	none	50–60	Cool fully; pops free
PETG	textured PEI	glue stick if over-gripping	80–90	Over-grips on smooth PEI; release layer essential
PCTG	smooth PEI	glue stick or PVP	70–90	Similar to PETG; release layer reduces sheet damage
ABS / ASA	smooth PEI	glue stick on first prints	95–110	Brim required for parts >100 mm; enclosure mandatory
HIPS	smooth PEI	glue stick	100–110	Limonene-soluble; brim for large parts
PP (unfilled, CF, GF)	PP-coated sheet or PP packing tape	Magigoo PP for difficult parts	85–105 (PP sheet) / 80–100 (tape) / 20 (cold-bed)	PP-on-PP self-adhesion; cool fully for release
PE / HDPE	PE-coated sheet or PP packing tape	Magigoo PP	80–100	Same principle as PP; sparse commercial PE-sheet availability
PA6 / PA66 / CoPA	G10 garolite	PEI + PVP as alternative	90–110	The garolite plate grips strongly; cool fully; CryoGrip Glacier also documented
PA12 / PA612 / PA11	smooth PEI	glue stick on demanding parts	70–90	Lower-shrinkage than PA6; PEI grips reliably
PA-CF / PA-GF	G10 garolite	Magigoo PA on PEI as alternative	90–110	High warp tendency tames best on garolite
PPA / PPA-CF / PPA-GF	smooth PEI + glue stick / PVP	Magigoo PC also works	90–120	G10 garolite acceptable; chamber temperature drives success more than surface
PC / PC blend	G10 garolite (long-term)	glue stick / PVP on PEI	100–115	Over-grips PEI catastrophically; release layer non-negotiable
PC-CF / PC-GF / ESD-PC	G10 garolite	Magigoo PC	100–120	Hardened nozzle mandatory; bed temperature near upper bound
PC/PTFE	smooth PEI	Magigoo PC	90–120	All-metal hotend required; chamber recommended
TPU / TPE	textured PEI	CryoGrip Glacier at 40–50 °C	40–60	Over-grips smooth PEI; release layer if smooth surface needed
TPEE	textured PEI	CryoGrip Glacier	50–70	Similar to TPU; higher bed than soft TPU

Polymer family	Best surface	Adhesive/release	Bed (°C)	Removal notes
PEBA	smooth PEI	none	50–60	Releases cleanly without adhesive; easier than TPU
PMMA	smooth PEI	glue stick	100–110	Brittle; thermal stress dominates; cool fully
POM	glass + glue stick or PA-class sheet	Magigoo PA	100–115	Low surface energy; brim mandatory; ventilation required
PVDF	smooth PEI	none	90–110	Adheres well; all-metal hotend; chamber for warp control
PPS-CF	G10 garolite	Magigoo PA	110–120	Active chamber 55–65 °C required; hardened nozzle mandatory
PEI / PEEK / PEKK	industrial adhesive	beyond prosumer scope	140–155	Industrial chamber required; outside this volume's scope
PVA / BVOH	smooth PEI	none	50–65	Print directly from a dryer; ambient air degrades quickly
PVB	smooth PEI	glue stick	70–80	Hygroscopic; dry before printing; IPA-smoothable after
PHA / PLA-PHA	smooth PEI	glue stick if cold-bed	0–60	PHA prints cooler than PLA; some products require unheated bed
PCL	glass + glue stick	tape	20–30	Very low T_m; minimal bed heating needed

Table 24.1 — Bed adhesion strategy by polymer family (consolidated reference). G10 garolite is the engineering default for any high-warp engineering polymer where the print would damage a PEI spring-steel sheet on removal; Magigoo's family of polymer-specific adhesives handles most remaining edge cases. Cold-bed approaches (PP, PCL, some PHA grades) use room-temperature bed during printing and elevated temperature only at end-of-print for release.

Three principles cut across the table. First, smooth PEI is the default surface for most polar polymers; textured PEI reduces grip and is preferred when over-grip damages the sheet on removal. Second, G10 garolite is the right answer for high-warp engineering polymers (PA6, PC, PPA, PPS) because it grips reliably during printing, releases cleanly on cool-down, and tolerates repeated thermal cycling without surface degradation. Third, polymer-specific adhesives (Magigoo PP, PA, PC) substantially outperform generic glue stick on the hardest filaments and are the engineering choice when print success rate is the metric.

24.2 Build-plate adhesives: the product landscape

Where Table 24.1 names an adhesive or release layer, the choice is rarely between brands that behave identically. Build-plate adhesives fall into four mechanical classes, and the class matters more than the label. **Glue sticks** are solid PVA: cheap, water-soluble, available anywhere, and adequate for PLA and basic PETG, but they wear after a handful of prints and apply unevenly. **Sprays** coat a large bed quickly and uniformly — useful for big first layers — at the cost of overspray onto the machine and a need for ventilation. **Liquid pen and brush adhesives** are the purpose-built tier: formulated to grip while the bed is hot and release as it cools, lasting many prints per application. **Temperature-activated adhesives** are a liquid sub-type whose grip rises with bed temperature, giving strong hold on hot beds and easy release once cool. Table 24.2 surveys the products a prosumer user is likely to encounter.

Product	Type	Material range	Notes
Magigoo Original	Liquid pen	PLA, ABS, PETG, HIPS, ASA, TPU	The default all-in-one. Pen applicator, holds hot and releases on cool-down, ~100+ applications per pen, cleans with water. The safest general-purpose choice for common filaments.
Magigoo PP / PA / PC	Liquid pen	Polymer-specific: PP, the nylon family, the PC family	Chemistry tuned per family. Magigoo PP is one of the few practical options for polypropylene; Magigoo PA and PC target the high-warp engineering polymers where generic glue stick fails.
Vision Miner Nano Polymer	Liquid brush	High-temp: PEEK, PEI, PPSU, PC, nylon; also PLA, PETG, ABS, HIPS, PVDF	The engineering-tier choice. 120 mL brush bottle, formulated for high-temperature materials, works on glass, PEI, and carbon surfaces; a single coat lasts many prints on lower-temp filaments.
Layerneer Bed Weld Original	Liquid	PLA, PETG, ABS, ASA, PVA, CPE — not nylon or PP	An aggressive adhesive aimed at stubborn corner-lift on large flat parts. The vendor explicitly does not recommend it for nylon or polypropylene.
Bambu Lab Liquid Glue	Liquid	PETG, TPU, and other common filaments	A clean liquid alternative to the glue stick; beginner-friendly, lower residue. Often used as a release layer on over-gripping plates.
TH3D Bed Cement	Liquid	Broad; works on PEI, flex plates, glass, garolite	100 mL bottle with an applicator tip, priced near half the leading brands. Grip is good for roughly three to four prints before reapplication.
Dimafix	Temp-activated pen	ABS, ASA, PC, PP, nylon and other high-warp materials	Grip increases with bed temperature and falls away as the bed cools. Pen format; favored for warp-prone engineering filaments.
3DLAC (and similar sprays)	Spray	PLA, PETG, ABS, ASA; nylon-specific variant available	Fast, uniform coverage on large beds. Overspray and ventilation are the trade-off; on very grippy stock plates it functions more as a release layer than an adhesive.
PVA glue stick (generic)	Solid stick	PLA, basic PETG; release layer for many materials	The budget baseline — washable, universally available, reapplied every few prints. A purple-tint stick shows coverage. Adequate for undemanding work and as a sacrificial release layer on PEI.

Table 24.2 — Build-plate adhesives accessible to prosumer users. Material ranges are as stated by each manufacturer; treat them as starting guidance, since adhesion also depends on bed surface, temperature, and first-layer settings. Sealed-ecosystem and industrial-only products are out of scope. Prices and formulations drift — Appendix D frames the brand landscape as point-in-time.

Two selection rules cover most cases. For **common filaments** — PLA, PETG, ABS, ASA, TPU — an all-in-one liquid pen such as Magigoo Original is the lowest-friction choice, and a PVA glue stick is the budget fallback; both grip adequately and release on cool-down. For **engineering filaments** — the nylon, PC, PPA, and PPS families, and anything in a heated chamber — a polymer-specific or high-temperature adhesive earns its cost: Magigoo's family-specific pens, Dimafix for warp-prone materials, or Vision Miner Nano Polymer for the highest heat tiers. A point worth keeping in mind from Table 24.1: with the highest-warp engineering polymers, the adhesive is not a substitute for the right build surface and chamber temperature — it is the last few percent of reliability on top of a correct surface choice, not a rescue for a wrong one. Finally, every product here is also a release agent: on a build surface that grips a given polymer too hard (PC or PETG on smooth PEI is the classic case), a thin adhesive layer protects the sheet by giving the part something sacrificial to bond to.

24.3 Build-plate types and the spring-steel ecosystem

Table 24.1 names a surface for each polymer; this section is the surface itself. Modern prosumer machines have largely converged on the flexible spring-steel system: a thin steel sheet, coated on one or both sides, held to the heated bed by an embedded magnet. The sheet flexes off the magnet after a print so parts pop free, and a machine's plate is really defined by its *coating*, not the steel. The coatings divide into six functional classes:

- **Smooth surfaces** — smooth PEI (a polymer film) and smooth-PEI-like coatings — give glassy-flat, glossy first layers and the strongest grip on polar polymers. That grip is the catch: PC, PETG, and PCTG over-adhere to hot smooth PEI and can tear the coating or pull fragments on removal, which is why Table 24.1 pairs them with a release layer.
- **Textured surfaces** — textured PEI, most commonly a powder-coated PEI steel sheet — trade gloss for a matte, lightly stippled first-layer finish and noticeably reduced grip, making them the safer default for over-gripping materials and for cosmetic parts where a matte underside is wanted.
- **Satin surfaces** sit between the two: a fine, even micro-texture that yields a soft semi-matte finish with grip closer to smooth than to coarse textured — a middle option for users who find smooth too grippy and textured too coarse.
- **Patterned plates** carry a decorative relief (woodgrain, geometric, marble-like) that transfers to the part's bottom face; they are a finish choice, with adhesion behavior tracking whatever base coating carries the pattern.
- **Engineering plates** are the high-temperature, high-warp tier: rigid G10/garolite and equivalent purpose-made sheets, used bare for PA, PC, PPA, and PPS because they grip those polymers hot and release cleanly on cool-down without a consumable adhesive.
- **Cold plates** are the inverse case — surfaces (and a workflow) for materials printed on an unheated or barely heated bed, such as polypropylene on a PP-faced sheet or PCL: adhesion is managed by surface chemistry and tape rather than bed heat, with the bed sometimes warmed only at end-of-print to aid release.

Surface class	Typical finish	Grip	Best-fit materials
Smooth PEI	Glossy, glass-flat	High on polar polymers	PLA, PVB, PEBA; PETG/PCTG/PC only with a release layer
Textured PEI (powder-coated)	Matte, lightly stippled	Moderate	PETG, PCTG, TPU, ABS/ASA; over-grip-prone materials generally
Satin	Soft semi-matte	Moderate-high	PLA, PETG, ABS — a middle option between smooth and textured
Patterned / decorative	Relief pattern in part underside	Tracks base coating	Cosmetic prints; adhesion follows whatever coating carries the pattern
Engineering (G10 / garolite)	Fine matte	High on engineering polymers; clean cool-down release	PA, PA-CF/GF, PC family, PPA, PPS-CF
Cold plate (PP-faced, tape, glass)	Varies by facing	Chemistry- and tape-driven, not heat-driven	PP and PP-CF/GF, PCL, some PHA grades

Table 24.3 — Build-plate surface classes. The class describes the coating's behavior; specific branded plates (below) are implementations of one or more of these classes. Grip is also a function of bed temperature and first-layer settings, so treat the column as a relative ranking rather than an absolute.

Within these classes, a few product families are common enough on prosumer hardware to name specifically. **G10 / garolite sheets** are a glass-epoxy laminate sold as flat rigid plates (Holden Enterprises and others) rather than flexible steel; they are the engineering-plate workhorse for the warp-prone polymers and tolerate repeated thermal cycling without coating wear. **BIQU CryoGrip** plates are flexible spring-steel sheets engineered around a cool-release effect — grip is strong while printing and falls away sharply as the plate cools, with the Glacier variant documented for TPU and for nylon at moderate bed temperatures; in slicer terms a CryoGrip sheet is treated as a high-temperature smooth-PEI-class plate and is kept within its rated temperature ceiling. **Prusa** ships three spring-steel sheets that map directly onto the classes above: a smooth PEI sheet, a textured powder-coated PEI sheet, and a satin sheet, plus a separate polypropylene-faced sheet for the cold-plate PP workflow. **Bambu Lab** plates follow the same pattern under different names — a textured PEI plate as the general-purpose default, a smooth/high-temperature plate for glossy first layers and higher-temperature engineering work, a cool-plate option for low-temperature materials, and an engineering plate intended for the warp-prone families. The naming differs by vendor, but the underlying surface classes in Table 24.3 are what actually determine behavior; matching the class to the polymer in Table 24.1 matters more than the brand on the box.

Three practical points. First, the coating is the consumable, not the steel: smooth PEI and powder-coated textured PEI both wear, and a release layer on over-gripping pairs (PC or PETG on hot smooth PEI) protects that coating directly — the §15.10 cost case for garolite on PC is exactly this. Second, surface class and bed temperature are coupled, not independent: the same plate grips harder hot, so a too-grippy result is sometimes a bed-temperature problem rather than a wrong-plate problem. Third, match the plate to the dominant material — a textured PEI sheet covers most common filaments, a bare engineering sheet earns its place the moment PA, PC, PPA, or PPS is in regular rotation, and a cold-plate or PP-faced sheet is effectively mandatory for polypropylene rather than optional.

25. Multi-material and dual-hotend printing

Multi-material printing extends FDM beyond single-color, single-polymer parts to functional combinations: rigid bodies with flexible seals, structural bodies with soluble supports, color-coded mechanical assemblies, and cosmetic models with mixed transparency. The hardware ecosystems implementing multi-material capability split into three architectures, each with distinct constraints on what can be combined.

25.1 Three hardware architectures

Single-extruder multi-material (MMU) systems share one nozzle across multiple filament feeds via an upstream switching mechanism. Filaments swap by retracting the active filament, advancing the new filament through the cutter or splicer, and purging the melt zone before resuming the print. The architecture is mechanically simple and cost-effective but introduces a substantial purge tax: typical purge volumes per swap are 50–200 mm^3, accumulating quickly across a multi-color print to volumes that may exceed the model itself. Chamber compatibility between filaments is also a hard constraint — every loaded filament must tolerate the chamber temperature dictated by the highest-temperature material in the print.

Dual-hotend systems mount two independent hotends on a shared toolhead. One hotend lifts out of the way while the other prints. Filament swaps require only switching which hotend is active — no purge, no melt-zone contamination. The cost is mechanical complexity and additional calibration: hotend offset (XY and Z) must be characterized for each machine. Dual-hotend systems support combinations that MMU cannot, because the two filaments never share a melt zone — different temperature windows, different filler systems, even incompatible materials can be combined.

IDEX (Independent Dual EXtruder) systems mount two complete toolheads on independent gantries, enabling true parallel printing — two parts at once, or one part with simultaneous deposition of two materials. The cost-of-ownership and footprint are highest in this tier; the throughput advantage is meaningful for batch production.

25.2 Material compatibility groupings

Filaments in any multi-material print must share a compatible chamber temperature envelope. Three practical tiers:

Tier	Chamber temp	Compatible filaments
Low	ambient – 35 °C	PLA, PVA, BVOH, PVB, PHA, PCL — and TPU/PEBA with care
Mid	35 – 50 °C	PETG, PCTG, ABS, ASA, HIPS, PA12, PA612, PP, PE — and PLA at the lower end
High	50 – 65 °C (active)	PC, PC-CF, PA6, PA6-CF, PPA-CF, PPS-CF, PEI-CF — and ABS/ASA at the lower end

Table 25.1 — Material compatibility groupings by chamber temperature. Mixing across tiers risks deforming the lower-temperature material (TPU softens above 50 °C; PLA softens above 55 °C). Filaments at tier boundaries may be mixed downward (run high-tier material at low-tier chamber if the geometry permits) but not upward.

25.3 Support filament strategies

Support material is the most common multi-material application. Three strategies dominate:

Soluble supports (Chapter 20) — PVA paired with PLA, BVOH paired with PLA/PETG/ABS — dissolve away in a water bath after printing. Highest geometric capability (internal cavities, undercuts, trapped supports) at the highest cost (purge tax, dissolution time, filament cost).

Same-material supports use the same filament for both model and support, distinguishing them via geometry (sparse infill, thin walls, spaced from the model surface). No filament cost premium; removal requires mechanical separation. The default approach for single-extruder FDM without multi-material capability.

Breakaway interface supports — vendor-specific products like Polymaker PolySupport or specialty PPA-compatible breakaway filaments — print as the support body but with a deliberately weak bond to the model material. Snap apart on cool-down. The middle ground: lower cost than soluble supports, better surface finish than same-material supports.

Hybrid strategies are common in production work. A PC-blend model with PCTG-interface layers on top of HIPS body supports — the HIPS bulk carries the structural support load, the PCTG interface releases cleanly from the PC body without limonene dissolution, and the support volume cost is HIPS rather than premium PCTG.

25.4 Purge cost economics

Single-extruder multi-material printing on a four-color part with 100 filament swaps and a 100 mm^3 purge per swap consumes 10,000 mm^3 of purged material — roughly 12 g for a 1.24 g/cm^3 polymer. For a small model the purge weight may exceed the model weight. Mitigations: reduce purge volume per swap (calibrate against actual cross-contamination; many systems use higher default purge than necessary); design the model to minimize swaps (color blocking rather than fine detail); use dual-hotend hardware which eliminates purge entirely for filament transitions; or accept the purge cost as the price of color capability.

26. Post-processing strategies

Post-processing converts a raw FDM print into a finished part. The techniques cluster into five categories — mechanical, chemical smoothing, coating, heat treatment, and assembly — each with polymer-specific compatibility constraints. The single most important reality from the per-polymer chapters: the same chemistry that drives a polymer's engineering value typically forecloses solvent-based finishing on that polymer.

26.1 Mechanical finishing

Sanding, polishing, and machining work on every FDM polymer with the right abrasive and the right technique. Three principles: **wet over dry** minimizes airborne particles (essential for CF/GF-reinforced grades where fiber fragments are documented respiratory hazards); **progressive grit** from coarse (220) through medium (400, 600) to fine (1000, 2000) produces the smoothest finish without skipping steps; **polymer-specific temperature awareness** matters — PLA, PETG, and PCTG smear under friction heat from power tools while POM, PC, and PPS tolerate aggressive sanding without deformation. For optical clarity on PCTG and PMMA: sand wet through 2000 grit, then polish with plastic-polish compound. For matte finish: stop at 800–1000 grit.

26.2 Solvent smoothing

Vapor smoothing and bath smoothing in compatible solvents produce glass-smooth surfaces by surface-only re-melting the printed bead structure. The compatibility matrix is narrow:

Polymer	Compatible solvent	Method	Hazard tier
ABS, ASA	Acetone	Vapor smoothing in closed container with brief warm-vapor exposure	Flammable; ventilation required
HIPS	Limonene; acetone	Bath dissolution; vapor smoothing also works	Skin sensitizer (limonene); flammable (acetone)
PVB	Isopropyl alcohol	Vapor or bath; vendor-recommended workflow	Low; household-tier solvent
PLA	No common workshop solvent works	Heat-gun gloss possible; mechanical only for matte	—
PETG, PCTG	No effective vapor solvent	Mechanical only; XTC-3D / 2K epoxy for gloss	—
PC, PC blend	Dichloromethane (DCM)	Bath or vapor; produces strong solvent-weld bond	OSHA carcinogen; fume hood mandatory
Nylons (PA, PPA)	No common workshop solvent works	Mechanical only; surface coatings for gloss	—
PP, PE	No workshop solvent at room temp	Mechanical only; flame treatment for paint adhesion	—
TPU, TPE, PEBA	No effective vapor solvent	Mechanical only; coatings limited by flexibility	—

Table 26.1 — Solvent-smoothing compatibility by polymer family. Most engineering polymers in this volume have no practical workshop-solvent smoothing route — the chemical resistance that drives their engineering value forecloses chemical finishing.

Mechanical finishing and coatings (2K epoxy, XTC-3D) are the practical routes for PETG, PCTG, nylons, polypropylene, and the high-performance specialty polymers.

26.3 Coatings and paint

Surface coatings cover three application classes: **gloss and fill** (XTC-3D, 2K epoxy clearcoats, plastic-bonding primers fill layer lines and produce smooth painted surfaces); **color and aesthetics** (automotive primers and topcoats over polymer-compatible bonding primers); **function** (conductive coatings for ESD, vapor barriers, anti-static treatments, UV protective clears for outdoor parts). Low-surface-energy polymers (PP, PE, POM) require flame treatment or polymer-specific primers (3M 4298UV, Loctite 770) before any coating will adhere reliably; standard automotive primers fail to wet these surfaces. Higher-surface-energy polymers (PLA, PETG, PCTG, ABS, ASA, PC) accept standard primer-topcoat workflows directly.

26.4 Heat treatment (annealing)

Annealing serves different purposes for amorphous and semi-crystalline polymers. For amorphous polymers (PETG, PCTG, ABS, ASA, PC), annealing relieves residual stress from rapid layer cooling — modest improvement to dimensional stability and creep resistance, no change to HDT. Temperature must stay below T_g by 10–15 °C to avoid distortion; typical schedules 60–100 °C for 2–4 hours depending on polymer. For semi-crystalline polymers (PLA, PA, PP, PPA, PEEK), annealing develops crystallinity — substantial gains in HDT and stiffness, dimensional change of 1–3% as the polymer chains pack into ordered regions. Schedule must stay above T_g but below T_m. Per-polymer detail in §3.6 and the polymer chapters; the unfilled-PPA exception in §14.9 is the most important caveat (warp during the heat soak carries through to the final part).

26.5 Assembly: gluing, fastening, inserts

Solvent welding dissolves both mating surfaces in a compatible solvent, then evaporates to leave a polymer-continuous bond. Works for ABS (acetone), PC (DCM), and PMMA (DCM or specialty acrylic solvents). **Adhesive bonding** covers everything else: cyanoacrylate (CA) for fast assembly of most polar polymers; epoxy (2K) for high-strength structural bonds; polyurethane for elastomer-to-rigid bonds; specialty polyolefin adhesives (Loctite Plastic Bonder, 3M 4298UV-primer + CA) for PP and PE bonding. **Mechanical fastening** avoids the adhesive problem entirely: heat-set threaded inserts (brass inserts with a knurled exterior that engages the printed plastic) work on PLA, PETG, PCTG, ABS, ASA, PC, nylons — any polymer with a reasonable melt window. Self-tapping screws work on fiber-reinforced filaments where the matrix grips threads reliably. **Press-fit and snap-fit** assemblies leverage polymer-specific elasticity: PETG, PCTG, PP, and nylons hold snap-fits through many cycles; PLA and PC fracture rather than yielding.

27. Cost and procurement landscape

Filament cost spans four orders of magnitude across the polymers in this volume — from $15/kg commodity PLA to $500/kg PEEK-CF. The cost tier drives procurement strategy as much as the technical specifications do.

27.1 Price tiers (early 2026, 1 kg / 1.75 mm retail)

Tier	Range ($/kg)	Representative products
Commodity	15–25	PLA, PETG, generic ABS, generic ASA, HIPS, generic CoPA, eSun/Sunlu budget brands
Mid-engineering	25–50	PCTG (Spectrum, 3D-Fuel, Fiberlogy), PolyMax PETG, PolyMax PC, Bambu PC, Prusament PETG, ASA premium brands, unfilled PA12
Engineering	50–100	Prusament PC Blend, PA-CF (Polymaker, Bambu), TPU 95A premium (NinjaTek, Polymaker), PVDF entry-tier
Specialty	100–250	PA-CF premium, PPA-CF (Bambu, 3DXTech), PPS-CF, ESD-PC, FR-PC, PEBA (3DXTech, Forward AM), PVDF specialty grades
Ultra	250–500+	PEEK, PEKK, PEI 1010-CF, Prusament PC Space Grade Black, ThermaX PSU/PPSU, specialty industrial-grade products

Table 27.1 — Filament price tiers (early 2026 retail; ±20% drift typical across regions and bulk quantities). The cost step from commodity to mid-engineering is roughly 2×; from mid-engineering to engineering is another 2×; from engineering to specialty is 3–5×; from specialty to ultra is another 2–4×. Procurement decisions should map the cost tier to the application's binding constraint.

27.2 Quality signals and vendor selection

Three observable signals distinguish quality manufacturers from budget-tier producers, often more reliably than price alone:

Diameter tolerance. ±0.02 mm is the engineering-grade target for 1.75 mm filament. ±0.03 to ±0.05 mm is acceptable for commodity use; looser than ±0.05 mm produces visible extrusion-rate variation in the printed bead. **Batch consistency.** Vendors that publish lot codes and provide consistent color and mechanical properties across batches are the engineering-grade choice; budget brands often show batch-to-batch color drift and mechanical variance. **TDS depth.** Published TDS data — particularly printed-specimen tensile values, not just resin-grade values — distinguishes engineering-oriented vendors from marketing-oriented ones. The depth and specificity of the TDS correlates strongly with the underlying product consistency.

27.3 Recycled-content programs

A growing set of vendors offer recycled-content products that the makers position as close to virgin material on the headline engineering metrics, though independent comparison is limited and reprocessing history affects any given batch. **3D-Fuel ReFuel** reprocesses post-industrial PCTG, with the vendor reporting retention of the ISO 527 tensile envelope of virgin Pro PCTG. **Fiberlogy R PP** is 100% post-consumer/post-industrial polypropylene with vendor-documented mechanical properties matching virgin Fiberlogy PP. **Braskem FL900PP-CF** uses 100% recycled carbon fiber feedstock in the PP matrix. **Polymaker PolyTerra PLA** is carbon-offset PLA shipped on paper rather than plastic spools. **Fillamentum Porthcurno / Fishy Filaments** offers ocean-recovered PP-GF. These products are real progress over straight virgin filament; treat them as marginal improvements to mainstream procurement rather than as license to print wastefully.

27.4 Procurement strategy by use case

Hobbyist or casual user: stick to commodity and mid-engineering tiers (PLA, PETG, PCTG, basic PC blend, TPU 95A) and one or two budget-tier brands plus one engineering-tier brand for reference. Buy in 1 kg spools; bulk procurement doesn't pay back unless the print volume supports it. **Maker space or prototyping shop:** standardize on engineering-tier brands (Prusament, Bambu, Polymaker, Spectrum) for predictable results; budget tier as a secondary option for cosmetic work. Bulk 2.5 kg spools and 5 kg refills are cost-effective. **Engineering qualification or production work:** specialty-tier and engineering-tier brands with published TDS data are mandatory; bulk procurement of specific batch codes preserves repeatability. The cost step up the tier ladder is usually worth it for parts that will be tested or certified.

28. Tribological filaments

Tribological filaments are engineered for parts whose binding constraint is wear at a moving interface — gears, bushings, cams, slides, bearing surfaces, guides. The relevant failure mode is not fracture under load or creep at temperature but the gradual loss of material and dimensional accuracy as two surfaces rub. The polymers covered in this chapter appear elsewhere in the volume under their chemistry families — iglidur tribo-grades are PA-based (Chapter 13), PC/PTFE is a polycarbonate composite (Chapter 15), POM is its own family (Chapter 17) — but the tribological use case cuts across all of them, which is why it earns a cross-cutting chapter rather than living inside any single polymer family. This chapter consolidates the wear-grade options and gives the vocabulary needed to choose between them.

28.1 A short tribology primer

Four parameters govern whether a printed part survives in a wear application. Specifying a tribo filament without understanding them is guesswork.

Coefficient of friction (COF). The ratio of friction force to normal force at a sliding interface, reported as a dynamic value (sliding) and a static value (breakaway). Low COF means less resistance, less frictional heating, and less energy lost in the mechanism. Engineering tribopolymers reach dynamic COF values of 0.10–0.25 against steel dry; unfilled engineering polymers like PA6 or PETG run 0.30–0.45. COF is not a fixed material constant — it depends on the counterface material, surface finish, load, sliding speed, and temperature — so vendor COF values are comparative indicators, not design allowables.

Wear rate (specific wear rate, k). The volume of material lost per unit of sliding distance per unit of normal load, with SI units of $mm^3/(N\cdot m)$. It is the single most direct measure of how long a wear part will last. Tribologically optimized polymers report k values one to two orders of magnitude below their unfilled base resin. A part that loses 0.05 mm of wall over a service life is functional; the same part in a high-k material loses 0.5 mm and fails on clearance or backlash.

PV limit. The product of contact pressure (P) and sliding velocity (V) defines the thermal-mechanical envelope of a sliding part. Every tribopolymer has a PV limit above which frictional heat generation outruns heat dissipation, the contact surface softens, and wear accelerates catastrophically. The PV limit is the reason a bushing that runs cool at low speed fails at high speed under the same load. Design wear parts to operate well below the published PV limit; FDM-printed parts should be derated further because layer-line porosity reduces thermal conductivity and the effective contact area is lower than a molded equivalent.

Counterface and lubrication regime. Tribological performance is a property of the pair, not the polymer alone. A polymer sliding against hardened steel behaves differently than the same polymer against aluminum, against another polymer, or against itself. Dry-running (self-lubricating) tribopolymers are formulated with solid lubricants — PTFE, silicone, graphite, or molybdenum disulfide dispersed in the matrix — so they need no applied grease or oil; this is the dominant use case for printed wear parts, because applied lubricant attracts grit and many printed mechanisms cannot be relubricated in service. Lubricated service (with grease or oil) lowers wear further but is rarely the design intent for FDM parts. Polymer-on-polymer pairs should mix chemistries — POM against PA, for example — because identical polymers in sliding contact tend to gall and adhesively transfer material.

An anisotropy caveat specific to FDM. A printed wear surface is not isotropic. Layer lines create a directional texture; sliding across the layer lines wears differently than sliding along them, and a surface formed by the top or bottom layer differs from one formed by the perimeter walls. Wherever possible, orient the part so the wear surface is formed by smooth perimeter extrusion rather than stepped layer banding, and expect a break-in period during which high asperities are worn flat before the steady-state wear rate is reached.

28.2 Wear-grade filament survey

The hobbyist-accessible tribological filament market clusters into four groups: dedicated tribopolymer compounds (the igus iglidur filament family), PTFE-modified composites of otherwise-conventional polymers, neat POM, and the carbon-fiber-reinforced engineering grades that deliver wear resistance as a side effect of stiffness.

Filament	Base / type	Tribological character	Best use
igus iglidur I150	PA-based tribopolymer with solid lubricant	Dry-running; low wear against steel and against itself; FDA-conformant grade	Gears, bushings, sliding parts in food-adjacent or general service
igus iglidur I180	Tribopolymer, higher-toughness grade	Dry-running; better impact tolerance than I150; slightly higher COF	Wear parts that also see shock loading or vibration
igus iglidur RW370 / J-class	High-temperature and specialty tribopolymer grades	Dry-running; extended PV envelope or temperature range per grade	Wear parts at elevated temperature or higher PV than I150 tolerates
PC/PTFE (e.g. Spectrum)	Polycarbonate matrix + dispersed PTFE	Low COF from the PTFE phase; PC matrix carries structural load and heat	Load-bearing wear parts that also need PC-class stiffness and HDT
POM (acetal — Gizmo Dorks, 3D-Fuel)	Neat polyoxymethylene	Low COF, excellent fatigue resistance, low and stable wear; no solid-lubricant additive needed	Gears, cams, low-friction mechanisms; the default printed-gear material
PETG-PTFE	PETG matrix + dispersed PTFE	Lower COF than neat PETG; modest wear improvement; easy to print	Light-duty sliding parts where PETG printability is wanted and loads are low
PA-CF wear grades	Carbon-fiber-reinforced nylon (PA6-CF, PA12-CF)	Wear resistance as a by-product of fiber stiffness; abrasive to the counterface	Stiff structural parts with incidental wear; not a first choice for pure bushings
PA + solid-lubricant blends	Nylon compounded with PTFE, MoS_2, or graphite	Dry-running; between neat PA and dedicated tribopolymers on wear	General wear parts where a dedicated tribopolymer is unavailable

Table 28.1 — Hobbyist-accessible tribological filaments. The igus iglidur filament family is the only group engineered specifically and solely for wear; the others deliver tribological performance as either a PTFE-additive modification (PC/PTFE, PETG-PTFE) or an inherent property of the base polymer (POM) or the reinforcement (PA-CF). Picking a CF-reinforced grade for a pure bushing application is a common error — the fiber that provides stiffness also abrades the metal shaft running inside it.

The iglidur filament family is igus's adaptation of its molded tribopolymer bushing materials to FDM filament form. The grades carry the same naming as the molded-part and bar-stock lines: I150 is the general-purpose dry-running grade and the most widely stocked; I180 trades a little wear performance for markedly better toughness; specialty grades extend the temperature or PV envelope. All are formulated to run dry — the solid lubricant is dispersed through the polymer, so a freshly printed part is self-lubricating with no break-in grease required. iglidur filament is the engineering default when wear is the primary design constraint and the part does not also need to carry a heavy structural load.

PTFE-modified composites — PC/PTFE and PETG-PTFE — take a conventional matrix polymer and disperse PTFE through it to lower the coefficient of friction. They are not equivalent. PC/PTFE keeps polycarbonate's stiffness, impact toughness, and ~110–140 °C service envelope, so it suits wear parts that also carry load or see heat; it demands an all-metal hotend and the PC-class process discipline of §15.7. PETG-PTFE is a light-duty material — it prints as easily as PETG and lowers friction usefully, but the wear improvement over neat PETG is modest and the PETG matrix limits it to low loads and near-room-temperature service. Treat PETG-PTFE as a friction-reduction convenience, not a true bearing material.

POM deserves its standing as the default printed-gear material. It delivers a low and stable coefficient of friction, excellent fatigue resistance under cyclic tooth loading, and a low wear rate without any solid-lubricant additive — the tribological behavior is intrinsic to the acetal chemistry. The trade-offs are covered in §17.2: difficult bed adhesion and a genuine formaldehyde-emission hazard that mandates ventilation. Where those can be managed, POM outperforms every PTFE-modified composite on gear and cam duty. POM against PA — acetal gear on a nylon gear, or acetal on an iglidur bushing — is a particularly good polymer-on-polymer pairing because the dissimilar chemistries resist galling.

28.3 Selecting and designing a wear part

Match the material to the dominant duty. **For gears and cams** — cyclic tooth contact, moderate load, the failure mode is tooth wear and rising backlash — POM is the first choice, with iglidur I150 the alternative when POM's bed adhesion or ventilation requirements cannot be met. **For plain bushings and sliding bearings** — continuous rubbing against a shaft, the failure mode is bore wear and growing clearance — a dedicated iglidur grade is the engineering answer; the dry-running formulation is exactly the design intent. **For load-bearing wear parts** — a slide or wear pad that also carries structural load or sees heat — PC/PTFE is the choice because the polycarbonate matrix supplies stiffness and thermal headroom that neither POM nor iglidur matches. **For light-duty low-friction parts** — a drawer slide, a low-load guide, a part where smooth motion matters more than service life — PETG-PTFE is adequate and the easiest of the group to print. **Avoid CF-reinforced grades for pure bushings**: the exposed carbon fiber abrades a metal counterface, and the application is better served by a dedicated tribopolymer.

Three design practices materially extend printed wear-part life. **Print the wear surface from perimeter walls, not layer banding** — orient the part so the sliding face is formed by smooth perimeter extrusion, which gives a more uniform surface and a lower steady-state wear rate. **Use high wall and infill density at the contact zone** — internal porosity beneath a wear surface reduces both load capacity and thermal conduction, pushing the part toward its PV limit sooner; solid or near-solid infill under bearing surfaces is worth the material. **Allow for break-in** — printed wear surfaces shed high asperities during the first hours of service before reaching steady-state wear, so size clearances expecting a small initial dimensional change, and where the application is critical, run a deliberate low-load break-in before putting the part into full service.

Cross-references: iglidur calibration values appear in Appendix B and the PA-family process guidance in §13.5; PC/PTFE process and the mandatory all-metal-hotend requirement are in §15.7; POM bed adhesion, the formaldehyde-emission hazard, and ventilation requirements are in §17.2 and §5.3.

Appendices

Cross-polymer property comparison tables, the author's bench-measured calibration profiles for a representative prosumer setup, an alphabetical brand index keyed to chapter references, and the consolidated source list for data values cited throughout the volume.

Appendix A — Master cross-polymer property comparison

Consolidated property tables across the polymer families in this volume. Values are typical FDM-printed-specimen envelopes from manufacturer TDS data, biased toward XY-direction tensile and modulus values where vendors publish them. Specific filament brands and batches will vary within each polymer's range by 10–25%. Cross-reference the per-polymer chapter for engineering decisions.

A.1 Thermal envelope

Polymer	T_g (°C)	T_m (°C)	HDT @ 0.45 MPa (°C)	Continuous service (°C)
PLA	55–65	150–170	55–60	50
PLA annealed (HTPLA)	55–65	150–170	~120	100
PETG	75–80	— (a)	70–75	60
PCTG	85–95	—	76–99	70
ABS	~105	—	90–98	80
ASA	~100	—	90–98	85
HIPS	90–100	—	85	70
PP unfilled	-10	160–170	85–100	60
PP-GF	-10	160–170	115–140	100
PP-CF	-10	160–170	115–160	100
PE / HDPE	-110	~130	50–60	60
PA6 (dry)	~55	215–225	150–170	80
PA66 (dry)	~70	255–265	180–200	100
PA12	~45	175–180	140–150	90
PA612	~50	210–220	150–160	100
PA11	~45	180–190	140–150	90
PPA (unfilled, filament)	~80	~230–260	75–85	70
PPA-CF (filament)	~80	~230–260	120–200 (c)	180
PC blend (general)	105–150	—	95–145	100
PC-CF	142+	—	140	130
ESD-PC	143	—	135–138	120

Polymer	T_g (°C)	T_m (°C)	HDT @ 0.45 MPa (°C)	Continuous service (°C)
PEI 9085-CF	186	—	180	170
PEI 1010-CF	217	—	210	200
PEEK	143	343	160 / 240 annealed	250
PEKK-A (amorphous)	~165	—	160	150
PPS-CF	~90	~280	200+	180
PMMA	80–110	—	94	70
POM	-60	165–180	100–120	90
PVDF	-35	165–175	110	120
TPU 95A	—	~200	50–70	70
TPEE 55D	—	~200	90–110	110
PEBA 40D	—	~200	80–95	90

Table A.1 — Thermal envelope across the polymer families covered in this volume. Continuous service temperature is engineering best practice (T_g minus 20–30 °C for amorphous; T_m minus 60 °C for semi-crystalline) — not the absolute upper limit, which is closer to T_g or HDT. Use this column for service-life calculations; use HDT for short-duration thermal events. (a) PETG is an amorphous copolyester with no true crystalline melting point; it is processed across a melt/processing range of roughly 230–250 °C rather than at a defined T_m. (b) The PEKK row is the amorphous grade (PEKK-A); semi-crystalline PEKK runs a higher continuous-service envelope of roughly 220–240 °C, as noted in §19.4. (c) The PPA rows give printable filament-grade values: commercial PPA filaments are printability-modified semi-aromatic copolymers with a melting point near 230–260 °C, well below the 290–320 °C of neat high-temperature PA6T/PA9T resins. PPA-CF HDT is strongly load- and anneal-dependent — roughly 120 °C at 1.80 MPa rising to ~200 °C at 0.45 MPa after annealing — so the filament datasheet should be read with the test basis in mind.

A.2 Mechanical envelope (XY-direction, dry as-printed)

Polymer	Density (g/cm^3)	Tensile (MPa)	Modulus (GPa)	Elongation (%)	Notched Izod (kJ/m^2)
PLA	1.24	50–70	3–4	3–8	2–4
PETG	1.23–1.27	40–50	1.9–2.1	8–25	4–8
PCTG	1.18–1.23	44–58	1.5–1.6	~220	~8–24 (b)
ABS	1.0–1.1	30–45	~2	10–40	15–25
ASA	1.05–1.1	30–45	~2	10–35	15–25
PP unfilled	0.90–0.91	15–25	1.0–1.4	100–600	5–15
PP-GF (15–30%)	1.05–1.15	30–50	2.0–3.0	3–10	7–12
PP-CF (15–30%)	0.91–1.00	25–45	2.0–4.0	3–6	10–15

Polymer	Density (g/cm^3)	Tensile (MPa)	Modulus (GPa)	Elongation (%)	Notched Izod (kJ/m^2)
PA6 dry	1.13	70–85	2.0–3.0	30 / 5 (Z)	5–8
PA12	1.01	45–55	1.1–1.5	30–80	4–6
PA6-CF (15–25%)	1.15	90–130	5–9	3–6	8–12
PPA-CF (15–20%)	~1.20	120–170	6–10	2–5	6–10
PC blend	~1.20	40–65	~2.0–2.5	6–80	50–80
PC-CF (10–15%)	~1.25	64–76	~5	~3	15–30
PPS-CF (10–20%)	~1.30	90–110	5–12	~2	~5
PEEK unfilled	1.30	90–100	3.5–4.0	30–50	5–7
PEEK-CF (15–30%)	1.35	130–170	12–15	~2	5–8
PMMA	1.18–1.20	60–75	3.0–3.5	2–5	~2
POM	1.4	65–75	2.5–3.0	10–30	6–8
PVDF	1.75–1.80	35–50	1.5–2.5	50–200	10–15
TPU 95A	1.20–1.25	30–45	~0.05	400–600	—
PEBA 40D	1.01	35–55	~0.08	400–700	—

Table A.2 — Mechanical envelope across the polymer families. Reinforced grades (CF, GF) carry the highest stiffness numbers but the lowest elongation and notched impact — the brittle/stiff trade is structural. Elastomer modulus values are reported low because the polymer flexes under test load; tensile strength remains useful as a relative metric even though elongation dominates elastomer applications. (b) PCTG notched-impact figures vary widely with test method (ISO 180 Izod vs ISO 179 Charpy) and print orientation; the ~8–24 kJ/m^2 range spans vendor TDS values near the low end and independently measured flat-printed specimens near the high end. Treat it as orientation- and method-dependent, not a single allowable.

A.3 Process envelope

Polymer	Nozzle (°C)	Bed (°C)	Chamber	Drying	Tier
PLA	200–220	50–60	none	45–55 °C, 4–6 h (optional)	1
PETG	230–250	80–90	optional	60–70 °C, 4–6 h	1
PCTG	240–270	70–90	optional	65–70 °C, 4–6 h	1
ABS / ASA	240–270	95–110	enclosed	60–70 °C, 4–6 h	2
PP family	200–280	20–105	optional	unfilled: not required; GF/CF: 60–80 °C, 4–6 h	2
PA12 / 612 / 11	245–280	60–90	enclosed	70–80 °C, 8–12 h	2

Polymer	Nozzle (°C)	Bed (°C)	Chamber	Drying	Tier
PA6 / 66	260–290	90–110	passive 40–50	80–90 °C, 10–16 h	2
PA-CF / GF	265–295	90–110	passive 40–50	90–110 °C, 8–10 h	2
PPA (unfilled)	275–310	80–110	passive 40–60	80–140 °C, 4–12 h (d)	3
PPA-CF / GF	280–320	90–120	active 55–65	80–140 °C, 4–12 h (d)	3
PC blend	270–290	100–115	passive 40–50	80–100 °C, 6–8 h	2
PC-CF / GF / ESD	275–300	100–120	passive 45–60	90–110 °C, 8–10 h	3
FR-PC	240–280	90–110	passive 40–50	60–80 °C, 4–16 h	2
PPS-CF	320–350	110–120	active 55–65	80–110 °C, 6–8 h	3
PEI-CF	350–390	140–155	active 65	130–150 °C, 4–6 h	3–4*
PEEK / PEKK	380–440	140–155	active 85+	120–130 °C, ≥4 h	4
PMMA	240–270	100–110	enclosed	90 °C, 4–6 h	2
POM	210–230	100–115	optional + ventilation	80 °C, 4–6 h	2
PVDF	230–250	90–110	optional	80 °C, 4–6 h	2
TPU / TPE	220–250	40–70	optional	50–65 °C, 4–6 h	1
TPEE	230–250	50–70	optional	65–75 °C, 6–8 h	1
PEBA	225–250	50–60	optional	70–80 °C, 6–8 h	2
PVA / BVOH	195–225	50–65	none	45–60 °C, 8–12 h	1
PVB	215±10	70–80	none	45 °C, 8 h	1

*Table A.3 — Process envelope and hardware tier across the polymer families. The tier column maps to the §4 hardware definitions: Tier 1 baseline desktop, Tier 2 engineering desktop, Tier 3 active-chamber engineering, Tier 4 ultra-high-temperature industrial (beyond prosumer scope). Filament selection outside the hardware's tier capability produces unreliable results. *PEI-CF straddles the Tier 3/Tier 4 boundary: it prints in a Tier 3 active chamber, but its 140–155 °C bed and 350–390 °C nozzle exceed the Tier 3 envelope defined in §4 (bed ≤120 °C) and require Tier 4 thermal hardware. Treat it as boundary hardware, not standard Tier 3. (d) PPA drying guidance varies by brand: the upper end (~140 °C, 8–12 h) suits the higher-melting engineering PPAs such as Bambu PPA-CF, while the printability-modified grades such as Siraya Fibreheart PPA specify a milder 80–100 °C for 4–6 h and treat drying as needed only when moisture symptoms appear. Follow the spool's own datasheet rather than a single family schedule.*

Appendix B — Example calibrated filament profiles

Bench-measured calibration values for specific filaments, captured on a representative prosumer setup as worked examples of the §23 calibration workflow. These values are **measured**, not vendor-supplied; they should be treated as starting points for re-calibration on the reader's actual hardware rather than as universal values. Spool-to-spool drift of 5–10% on EM and PA is normal within the same brand and color.

B.1 Reference hardware setup

All values below were measured on a single enclosed CoreXY prosumer printer with a 0.4 mm hardened-tip nozzle (PCD-tipped for the CF-loaded and abrasive grades, hardened steel for the unfilled engineering polymers), in an active-chamber configuration capable of 45–55 °C ambient. Per-spool drying was performed to the §3.5 protocol before each calibration. The calibrations reported here used the Califlower Mk2 XY-shrinkage methodology and the 12-sample wall measurement EM method described in §23.4. Where a different nozzle size was used (0.6 mm high-flow), it is noted in the per-profile entry.

B.2 Calibrated profiles (engineering polymers)

Filament	Nozzle (°C)	Bed (°C)	Max vol. (mm^3/s)	EM	PA	XY shrink (%)
Prusament PC Blend	275	110	~10	1.045	0.025	—
Prusament ASA (in progress)	260	105	9.5	1.030	pending	pending
Kexcelled K8 PC	270	105	~10	1.049	0.045	—
3D-Fuel Pro PCTG	265	85	~10	0.937	0.053	0.20
Spectrum PCTG Matte Black CF (0.4 mm)	245	85	11	0.960	tuned	0.20
Overture Easy Nylon (CoPA)	245	50	11	1.000	0.030	0.25
Polymaker Fiberon PA6-CF20	290	95	~9	0.898	tuned	0.20
iglidur I150-PF (PA6 tribological)	245	60	4	1.030	0.01–0.06	—
Siraya Tech TPU 64D	260	45	5	0.970	tuned	—

Table B.1 — Bench-measured calibration profiles on a 0.4 mm PCD-tipped or hardened-steel nozzle. Bed surface varies by polymer family per §24; the values above assume the bed surface from that chapter's recommendation. The Prusament ASA profile is in progress at compilation; pressure advance and XY shrinkage are pending.

B.3 Calibrated profiles (0.6 mm high-flow nozzle)

Filament	Nozzle (°C)	Bed (°C)	Chamber (°C)	Max vol. (mm^3/s)	EM	PA
Overture ASA (0.6 mm HF)	265	95	45	14	tuned	0.025
Polymaker Fiberon PET-GF15 (0.6 mm HF)	290	80	55–60	13	tuned	0.030
Polymaker Fiberon PPS-CF10 (0.6 mm Diamondback)	350	120	55–65	~10	tuned	tuned

Table B.2 — 0.6 mm high-flow profiles where the larger nozzle was used instead of the 0.4 mm default. Overhang fan settings: 40% for PET-GF15 (reduces stringing on the longer-melt high-flow setup); 0% for ASA and PPS-CF (interlayer adhesion sensitive to cooling at this nozzle scale).

B.4 Notes on workflow

Pressure advance is best stored per-filament rather than as a single machine-wide value, so the correct compensation travels with the material instead of requiring a manual reset between filaments. Most firmware implementations expose a way to do this: a per-filament start-G-code command (for example, `M900 K…` on Marlin, `M572 D0 S…` on RepRapFirmware and Prusa Buddy firmware, or the `SET_PRESSURE_ADVANCE` macro on Klipper), or a per-filament field in the slicer profile on printers that manage the value in firmware. The profiles above were captured with the value in the filament start G-code; the reader should use whichever mechanism their own firmware and slicer provide. Skew correction, where the frame is measured out of square, is applied either in firmware or as a G-code post-processing step and validated against a printed skew calibration model; the residual after correction on the reference setup was below 0.02°. Z-shrinkage compensation was intentionally skipped on most profiles where Z-axis dimensional precision was already within the engineering tolerance for the intended application; it is worth measuring only where tall parts must hold a tight Z dimension.

Appendix C — Brand index

Alphabetical index of filament brands cited in this volume, with their primary product families and the chapter references where they appear. Brands with single-chapter coverage are listed once; brands spanning multiple polymer families are listed with the primary application axis noted.

Brand	Primary product families	Chapters
3D-Fuel	Pro PCTG (Tritan), ReFuel PCTG, PETG, PLA	6, 7, 8
3DXTech	CarbonX (PEEK, PEKK, PEBA, PA6-CF, PC-CF, PPS-CF, HTN, PETG-CF); ThermaX (PEEK, PEKK, PEI 9085-CF, PEI 1010-CF, PSU, PPSU); FluorX PVDF; 3DXSTAT ESD-Safe PC; FibreX PPA+GF15	13, 14, 15, 16, 17, 18, 19
American Filament	PCTG, PETG (US food-contact focus)	8
AzureFilm	PC-ABS, PETG, PLA, ABS (European budget tier)	15
Bambu Lab	PC, PC FR, PPS-CF, PPA-CF, PAHT-CF, PA6-CF, PA6-GF, TPU 95A, TPU for AMS, Support W	13, 14, 15, 16, 18, 20
BCN3D	PAHT CF15, BVOH; primarily for BCN3D printer ecosystem	14, 20
Braskem	FL900PP-CF (recycled CF), FL500PP-GF, FL100PP, FL105PP, FL300PE	11, 12
colorFabb	LW-PLA, PLA/PHA, allPHA, nGen copolyester	6, 7, 21
Creality	Generic "Nylon" SKUs (CoPA / PA6 base), budget engineering filaments	13
eSun	PVA, eTPU-95A, generic Nylon (CoPA), generic engineering filaments (budget tier)	13, 16, 20
Essentium	PCTG (Tritan)	8
Fiberlogy	PCTG, Nylon PA12, PA12-GF, PP, R PP (recycled), Inox metal-filled	7, 8, 11, 13
Fillamentum	PP 2320, Porthcurno PP-GF (ocean-recovered), NonOilen PLA/PHA, PMMA	11, 17, 21
Flashforge	PPS-CF (LUVOCOM), PPA-CF, PEEK (limited)	14, 18, 19
FormFutura	AthenaX (PCTG-class), ApolloX (ASA), TitanX (ABS), Centaur PP, Atlas Support	7, 10, 11, 20
Forward AM (BASF)	Ultrafuse PC/ABS FR, PC GF30, TPU 64D/85A/95A, PEBA	15, 16
Gizmo Dorks	Acetal (POM)	17
Kexcelled	K8 PC, K-class PLA and engineering grades	15
Nanovia	PC family (PC-CF and PC-ABS variants); French specialty	15
NinjaTek	NinjaFlex 85A, Cheetah 95A, Armadillo 75D	16
Nobufil	PCTG, color-focused European specialty	8
Overture	Easy Nylon (CoPA), ASA, PETG, generic engineering	10, 13

Brand	Primary product families	Chapters
Polymaker	PolyMax PC, PolyLite PC, PC-ABS, PC-PBT, PolyMide CoPA, Fiberon PA6-CF20, PA612-CF15, PA6-GF25, PPS-CF10, PolyFlex TPU, PolyMax TPU, PolyDissolve S1, PolyTerra PLA, PolyMax PETG	6, 7, 13, 15, 16, 18, 20
PPprint	P-filament 721, P-support 279, P-surface 141 (PP system)	11
Prusament	PC Blend, PC Blend CF, PC Space Grade Black, ASA, PETG, PVB, PA11-CF Carbon Fiber, PP CF, PP GF, PLA	6, 7, 10, 11, 13, 15, 21
Qidi	PAHT-CF / PAHT-GF (PPA-based)	14
Raise3D	Industrial PPA CF, PPA GF, breakaway PPA support	14
Recreus	FilaFlex 60A/70A/82A/95A, PP3D, PP-GF	11, 16
SainSmart	TPU 95A, generic flexibles (budget tier)	16
Siraya Tech	Fibreheart PPA, PPA-CF, PPA-CF Core, Mecha PA6-CF, NylonPro CoPA, TPU 64D, Pro Flex 85A, foaming TPU line, Mushroom foaming PLA	13, 14, 16
Spectrum	Premium PCTG, PCTG CF10, PCTG GF, HDPE, PC CF, PC/PTFE, PC/ABS FR V0, PMMA, ABS, ASA, PLA	7, 8, 10, 12, 15, 17
Sunlu	TPU 95A, PETG, PLA, generic Nylon (budget tier)	7, 11, 13, 16
Tangled Filament	PCTG (aggressive pricing target)	8
Verbatim	Primalloy PVA, BVOH	20

Appendix D — Consolidated references

Source list for the data values, methodologies, and references cited throughout the volume. Per the editorial principle in §1.3, the citation hierarchy is manufacturer filament TDS first, resin manufacturer TDS second, peer-reviewed literature and independent testing third, with vendor marketing relegated to the bottom of the source stack. Where a stable canonical location exists, the URL is given below with the date it was last checked (May 2026). Filament technical datasheets are versioned and their document paths change with vendor website updates; for those, the manufacturer's official domain is given as the stable entry point rather than a deep link that will rot, and the reader should expect the live TDS to supersede any figure quoted here. This list does not claim per-claim version provenance: individual numeric values were drawn from whichever TDS revision was current during preparation, and that revision is not always recoverable. Treat the volume's figures as starting points to be confirmed against current vendor data, exactly as §1.3 and the Preface state.

D.1 Independent testing datasets

MyTechFun comparative filament test database. An independently compiled dataset of tensile, layer-adhesion, and thermal measurements for a large number of filaments, tested on a single reference machine with a uniform test geometry. It is a useful cross-brand sanity check on manufacturers' TDS-published values. The database is the property of its author and is distributed to the project's Patreon supporters; its specific measured values are not reproduced in this volume. Readers who want the underlying numbers should obtain them directly from the MyTechFun project (mytechfun.com and the associated Patreon), under that project's own terms. §13.7 and §14.11 discuss, in general terms, the patterns such independent testing reveals — datasheet stiffness overstating printed-part performance, and heat figures diverging by test method — without citing any of the database's figures.

Prosumer-printer community troubleshooting analysis. The author's statistical analysis of ~910 community-reported troubleshooting threads on a single prosumer printer model, classified into 15 issue categories. Cited in the polymer chapters as the empirical basis for the relative frequency of failure modes (VFA, layer adhesion loss, bed adhesion, warp) across polymer families. Method and classifier are documented in the author's published write-up; see the revision note in D.5 for where errata and supporting material are tracked.

Califlower Mk2 dimensional calibration methodology. A multi-feature XY-shrinkage test geometry published on community model repositories alongside the calibration methodology used throughout this volume. Provides both external and internal dimensional checks for shrinkage compensation tuning. The model and accompanying method notes are published on the author's Printables profile (accessed May 2026).

D.2 Manufacturer technical datasheets

Filament TDS data is cited from the manufacturers' published documents on their official websites and distributor portals. The principal manufacturer reference points used across the volume:

Manufacturer	Product families with TDS data cited
3D-Fuel	Pro PCTG, ReFuel PCTG
3DXTech	CarbonX, ThermaX, FluorX, 3DXSTAT product families
AzureFilm	PC-ABS

Manufacturer	Product families with TDS data cited
Bambu Lab	PC, PC FR, PPA-CF, PAHT-CF, PA6-CF, PA6-GF, TPU 95A
Braskem	FL900PP-CF, FL500PP-GF, FL100PP, FL105PP, FL300PE
Eastman	Tritan TX1001 resin TDS (foundational PCTG reference)
Fiberlogy	PCTG, PA12, PP, R PP
Fillamentum	PP 2320, PLA-PHA NonOilen
Forward AM (BASF)	Ultrafuse PC/ABS FR, PC GF30, TPU, PEBA
NinjaTek	NinjaFlex, Cheetah, Armadillo
Polymaker	PolyMax PC, PC-ABS, PC-PBT, Fiberon PA, PolyDissolve, PolyTerra, PolyMax PETG
PPprint	P-filament 721, P-support 279
Prusament	PC Blend, PC Blend CF, PC Space Grade, ASA, PETG, PVB, PA11-CF, PP CF, PP GF, PLA
Recreus	FilaFlex product line
Siraya Tech	Fibreheart PPA/PPA-CF/PPA-CF Core, TPU 64D, foaming product line
Spectrum	PCTG, PC CF, PC/PTFE, PC/ABS FR V0, HDPE, PMMA

Table D.1 — Manufacturer TDS sources by filament family. Each manufacturer publishes current technical datasheets on its official domain (e.g. bambulab.com, prusa3d.com, polymaker.com, 3dxtech.com, fiberlogy.com, spectrumfilaments.com, basf-forward-am.com, eastman.com); those domains are the stable entry point and were the live source checked May 2026. Deep links to individual TDS PDFs are deliberately not listed because vendors revise document paths frequently — but, unlike a prior revision of this appendix, the official domains above are given so the source is locatable. Where a datasheet states a version, the volume cites it inline (for example Table 14.6 cites the Bambu Lab PPA-CF TDS V1.0); where it does not, the figure should be treated as the revision current at the time of writing and reconfirmed against the live TDS.

D.3 Resin manufacturer reference data

Base-polymer TDS data is cited from the resin producers where the filament TDS is silent on a property of interest and the filament is clearly built on a documented resin grade. The principal resin producers referenced, with their official material-data domains (accessed May 2026):

- **Eastman** — Tritan, Amphora, Eastar copolyester grades (eastman.com; product catalog at productcatalog.eastman.com).
- **Covestro** — Makrolon polycarbonate (covestro.com / solutions.covestro.com).
- **SABIC** — Lexan PC, ULTEM PEI (sabic.com).
- **BASF** — Elastollan TPU, Ultramid PA, Ultrason PSU/PPSU (basf.com; Forward AM at basf-forward-am.com).
- **Arkema** — Pebax PEBA, Kynar PVDF (arkema.com; hpp.arkema.com for the Kynar fluoropolymer family).
- **Solvay / Syensqo** — Radel PPSU, Ryton PPS, KetaSpire PEEK, AvaSpire PAEK (syensqo.com, formerly solvay.com specialty polymers).

– **DuPont** — Zytel and Zytel HTN polyamides, Delrin POM (dupont.com; note Delrin and the HTN line have moved through divestitures and may appear under successor-company domains).
– **Victrex** — PEEK 450G and related grades (victrex.com).
– **Kuraray** — Genestar PA9T (kuraray.com).

Resin TDS and SDS documents on these domains are versioned; cite the version shown on the retrieved document for any audit use.

D.4 Standards bodies and occupational safety

Test-method standards are cited by their standard number, which is the stable identifier; full texts are obtained from the issuing body's catalog. **Mechanical testing:** ISO 527 (tensile), ISO 178 (flexural), ISO 179 / ISO 180 (Charpy / Izod impact); ASTM D638 (tensile), ASTM D790 (flexural), ASTM D256 (Izod) — ISO standards via iso.org, ASTM standards via astm.org. **Thermal testing:** ISO 75 / ASTM D648 (HDT), ISO 306 / ASTM D1525 (Vicat), ASTM D3418 (DSC), ASTM D955 (mold shrinkage). **Optical and surface:** ASTM D1003 (haze and transmittance), ASTM D785 (Rockwell hardness). **Flammability:** UL94 (flame test, via ulse.org), EN45545 (rail-vehicle fire-safety, via cen.eu / national standards bodies).

Indoor air and emissions. ANSI/CAN/UL 2904, "Standard Method for Testing and Assessing Particle and Chemical Emissions from 3D Printers" (first edition, 2019) — UL Standards & Engagement, ulse.org; background and the underlying UL Chemical Safety / Georgia Tech research at chemicalinsights.ul.org. NIOSH, "Approaches to Safe 3D Printing: A Guide for Makerspace Users, Schools, Libraries, and Small Businesses," DHHS (NIOSH) Publication No. 2024-103, at cdc.gov/niosh/docs/2024-103/. NIOSH Health Hazard Evaluation Report 2017-0059-3291, "Evaluation of 3-D printer emissions and personal exposures at a manufacturing facility," at cdc.gov/niosh/hhe/ (reports/pdfs/2017-0059-3291.pdf). All accessed May 2026.

Food contact and biocompatibility. U.S. FDA food-contact regulations under 21 CFR Part 177 (polymer-specific subparts), via ecfr.gov; NSF/ANSI 51 (food-equipment materials) and NSF/ANSI/CAN 61 (drinking-water system components), via nsf.org. FDA, "Technical Considerations for Additive Manufactured Medical Devices — Guidance for Industry and Food and Drug Administration Staff" (finalized 5 December 2017; docket FDA-2016-D-1210), via fda.gov. ISO 10993-1, "Biological evaluation of medical devices — Part 1: Evaluation and testing within a risk management process," via iso.org. All accessed May 2026. As §8.9 and §19.4 stress, food-contact and biocompatibility certifications attach to a resin grade or a cleared device and validated process — not to filament generically.

D.5 Editorial scope and revision context

This volume was compiled May 2026, with brand surveys current to early 2026 and calibration profiles measured on the author's prosumer hardware in 2025–2026. The polymer-chemistry foundations and process-physics principles will remain accurate; the brand surveys, price ranges, and specific product availability will drift and should be verified against current vendor data for procurement decisions. Errata and updates are tracked on the author's GitHub repository alongside the supporting calibration methodology and the associated slicer calibration-edition fork.

Appendix E — License and terms of use

Index

Polymer names, properties, processes, and chemistry terms with their primary page references — pages where the term receives substantive coverage rather than a passing mention. The brand index is Appendix C; this index covers materials and concepts. Every page number is an individual link to the referenced page.

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